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GEYSERS
JOHN S. RINEHART

"... the field is open for exploration - illimitable in resource, grand in extent, wonderful in variety, in a climate favored of Heaven, and amid scenery the most stupendous on the continent." Langford, 1871.

Introduction

Bunsen, of burner fame, and his associate Descloizeaux, made the first scientific studies of geysers during a journey to Iceland in 1846. (Bunsen, 1848; Descloizeaux, 1847) They did then what we do now: analyzed their waters for chemicals; probed their depths with primitive but effective and reliable maximum temperature thermometers; observed circulation patterns within their reservoirs; listened to their gurglings and detonations as instabilities developed; described ejection patterns of the water thrown out during eruptions; and finally, developed a geyser theory that still stands today. Both were clever experimenters, careful analysts and interesting writers. Bunsen's observation that the jets of water rotate during an eruption of the Great Geysir is pure serendipity (1848):

"The rotatory motion cannot certainly be observed through the dense clouds of vapour that envelop the erupted masses of water, but I accidentally discovered it in an experiment originally instituted with a view of measuring the pressure

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at the base of the geyser column during a great eruption, by means of a small maximum manometer, which was suspended by a line in the middle of the spring, and sunk very nearly to the bottom. A number of stones, which I sunk suspended to fine threads, that were secured at various parts of the circumference of the funnel, separated from the threads without being again erupted, however, with the water. The threads themselves, which were suspended round the circumference of the tube of the geyser, and parallel with the line at a distance of 1.5 meters, were wheeled into an inextricable coil around the line of the manometer, which could only arise from the gyratory motion in the column of water".

Gentlemen travelers, explorers, scientists, guides, a whole host of men have written about geysers and speculated on their behavior (Mackenzie, 1842; Langford, 1871; Hague, 1904; Fix, 1939; Vosburgh, 1940; Marler, 1964a; Haynes, 1966; Bonney and Bonney, 1970). Much of this literature is purely descriptive, extolling the beauties of the geysers, describing their geological settings, their external forms and basins, and their activity. Serious scientific study has been limited. In general it has followed Bunsen's early pattern of chemical analysis, thermometry, and fluid flow studies with newer techniques being applied as they became

available (Graton, Birch, and Kennedy, 1949; Fournier and Rowe, 1966; Nicholls and Rinehart, 1967; White, 1967; Rinehart, 1972a).

Beginning about the turn of the century, considerable interest developed in making models of geysers and several workable ones were built (Honda and Terada, 1906; Forrester and Thune, 1942; von Engeln and Hausman, 1916). One of the more successful is shown in Fig. 1 (Munby, 1902). It contains the three main elements of a geysers, heat source, water supply, and reservoir.

Geysering is understood in a general way. A reservoir of water as a result of being locally heated becomes unstable when its heat content reaches some critical level and distribution. At this time, abrupt and vigorous generation of steam occurs within the geyser, greatly modifying both temperature and fluid distributions, forcibly throwing water out of the geyser. The agitation lasts a while, then ceases, with the reservoir becoming stable, all set to begin a new cycle of instability.

It is the details of this cycle that need investigating. Geyser research applies itself to two main sets of problems: one concerned with the shape and dimensions of the reservoir, the source and quantity of water to fill it, and the nature and variation of the heat source; and a second set relating

to the processes by which the instabilities develop and relieve themselves.

The principal geyser areas in the world are in Yellowstone National Park in the United States (Allen and Day, 1935), Iceland, (Barth, 1950; Thorkelsson, 1940), Rotorura in New Zealand (Elder, 1966), Kamchatka in USSR (Gippenreiter, 1969), and Japan (Nomura, 1954), although there are numerous other geysers scattered here and there around the world. By far the most, a few hundred, are located in Yellowstone. Their beauty and unusualness make them popular attractions and subject them to exploitation and vandalism. Fortunately, the Yellowstone area was set aside as a national park shortly after its exploration (Bonney and Bonney, 1970) a hundred years ago. In Iceland, the geysers have been extensively tampered with by private individuals, and in New Zealand most of the geyser activity has been destroyed through the construction of geothermal power plants.

Geological setting of a geyser

Geysers are usually found in quaternary and tertiary volcanic areas typically in a well marked drainage basin or valley floor and often surrounded by the walls of a caldera (Allen and Day, 1935; Barth, 1950; Fisher, 1960; Waring, 1965; Keefer, 1972). It is easy to identify at least twenty such

calderas in Yellowstone. The basin is a mass of loose gravels sitting on heavily fractured and fissured rock which in turn apparently lies over a plug of hot magmatic rock. In the Upper Geyser Basin in Yellowstone which is occupied by many major geysers: Old Faithful, Beehive, Grand, Riverside, Lion, Giantess, drilling has indicated that the siliceous sinter is about 6 m thick, below which there is about 70 m of glacially emplaced rhyolite gravels underlain by fractured rhyolite (Fenner, 1936).

The geyser basins are excellent collectors of meteoric water some of which percolates down through the rocky mass where it is heated, becomes lighter, and, driven by its bouyancy, returns to the surface to heat geyser reservoirs and hot pools or escape as steam through fumeroles. These waters are generally clear and alkaline containing in addition to several hundred parts per million of silica, substantial amounts of bicarbonates and chlorides.

The rocks through which the hot water percolates are highly siliceous: in Yellowstone through fractured rhyolite. At Steamboat Springs, Nevada, where several geysers formerly were active, the water percolates through granite (Brannock, et al, 1948; White, 1968); at Beowawe, Nevada, through basalt (Nolan and Anderson, 1934); and in the one geyser in Japan, now inactive, through andesite (Honda and Terada, 1906).

A geyser system consists of a reservoir, kept filled by local ground water, perched on a large, several kilometers in extent, mass of fractured rock through which water circulates and feeds heat to the reservoir (Elder, 1966; White, 1967) (Fig. 2). The percolating water leaches out the silica and other minerals and then redeposits much of it as siliceous sinter to build geyser reservoirs and their associated hot water feeder systems (White, Brannock, and Murata, 1956; Noguchi, 1956; Iwasaki, 1962; Mahon, 1966). It is this sinter that builds up the exotic cones, terraces, and lined pools that characterize geyser fields. In general, silica is deposited because it is less soluble in cold water than in hot as indicated in Fig. 3. It is also left behind as the water evaporates. The rate of deposition is not known although numerous attempts have been made to measure it. Obviously it varies greatly from geyser to geyser depending upon the origin of the water in the geyser. It is certainly usually not rapid. During the hundred years that Yellowstone has been visited there have been essentially no detectable changes in the major surface features. On the other hand, during a twenty year period when the Great Geysir, Iceland, was dormant, a geyserite deposit 10 cm thick was formed in its bowl (Einarsson, 1967).

A geyser reservoir is usually complex and unfortunately

in most instances only the surface features can be ascertained, although some have been probed to great depths. Each geyser builds its own system of ducts, channels, cavities, and pools by depositing dissolved silica. For the most part, the major geysers do not appear to be intimately connected with each other near the surface (Allen and Day, 1935), although a few such as those near Grand in Yellowstone, obviously are (Bloss and Barth, 1949; Marler, 1951).

Properties of hot water and steam

The properties of water upon which geyser action depends are its decrease in specific gravity with increase in temperature, its increase in boiling point with increase in pressure, and its 1500 fold increase in volume when vaporized into steam. The change in specific gravity, plotted in Fig. 4, is the driving force that establishes and maintains circulation both within the geyser reservoir and throughout the geyser basin. The circulation brings heat up from deep within the basin to feed it to the geyser reservoir. Constrictions in the reservoir plumbing usually restrict circulation allowing instabilities to develop in which denser cooler waters overlies lighter warmer waters (Hales, 1937). Geyser action is precipitated when such instabilities can no longer be maintained (Murty, 1969).

Boiling point of water as a function of hydrostatic head

is plotted in Fig. 5 for standard atmospheric pressure, 760 mm of Hg. At the reduced atmospheric pressure surrounding the geysers of Yellowstone Park which lies at an elevation of 2204 m, the curve intersects the abscissa at 93° . Under a hydrostatic head, water remains in its liquid state to temperatures that greatly exceed its boiling point under no head at ambient atmospheric pressure. When circulation is restricted, a heated column or pool of water can develop a pattern of temperature differences with depth that can easily lead to intermittent, cataclysmic agitation of the water when steam bubbles suddenly form and subsequently collapse (Bloss and Barth, 1949). Bubble formation will occur whenever the temperature-depth profile curve crosses over the boiling point curve; if the bubbles then encounter cooler water as they rise, they will collapse.

The 1500 fold increase in volume which accompanies the flashing of water into steam is a potent mechanical force capable of drastically redistributing the water within a geyser reservoir. Both the gentle pulsation in water levels of pools and the explosively violent ejection of water from geysers are consequences of the actions of this force.

Hot pools, spouters, and geysers: how they work

The term geyser is derived from an old Icelandic verb,

gjósa, meaning to erupt. It usually refers to a reservoir of hot water which ejects part or all of its contents intermittently and violently. In most geyser areas, there is a full spectrum of activity ranging from quiescent hot pools to geysers, violently erupting pools, and dry steam jets.

There are many more hot pools than geysers since very unusual conditions must obtain if a hot pool is to erupt intermittently. In Yellowstone the ratio is about ten to one. Typically a hot pool consists of a basin of water which is being continuously heated and in which circulation is taking place freely. While temperature gradients exist in such pools and water rising to the surface can be often superheated a few degrees, a balanced and steady state situation is sustained between heat flow and water supply and pronounced instabilities do not develop. Hot, nongeysering pools exist either when the rate of heat input is too low to cause the inflowing water to boil or when the shape of the reservoir allows free convective circulation, permitting heat to be dissipated by continuous mild surface boiling.

A spouter develops when the rate of heat flow is exceedingly high relative to the amount of water in the pool. The superheated water and steam enter the reservoir, heating the water therein to a high temperature, which, when it rises to the surface, flashes into steam. The intimate connection

between hot springs and superheated water and steam can be clearly seen at the Growler Spring in Norris Basin in Yellowstone. Following wet weather, the crater fills with water and becomes a hot spring which boils and splashes. As the ground dries out and the water level falls, it becomes successively a spouter and then a dry steam jet. In Yellowstone, such steam jets are superheated to a temperature of about 138°C , implying that only 1 kg of steam is necessary to heat 6.4 kg of spring water to boiling (Allen and Day, 1935).

Intermittently erupting geysers fall into two distinct classes: fountain or pool; and columnar or cone. The eruption of a fountain geyser consists of a series of steam explosions resulting from blobs of superheated water rising to the surface and flashing into steam. Along with the steam, a small quantity of finely divided water droplets is thrown to sometimes great height. A photograph of such an explosion occurring at Solitary Geyser in Yellowstone is reproduced in Fig. 6, and one at Strokkur, Iceland, in Fig. 7. Hundreds of such explosions may occur with the episode lasting several minutes before the geyser settles back down. Very little water is thrown out since the action takes place so close to the surface.

Narcissus Geyser, near Firehole Lake in Yellowstone is a classic example (Rinehart, 1970a). Its hourglass vertical

cross section is about 3 m in diameter at the top, narrowing to a 0.6 m diameter pipe about 2 m down, and then opening up again toward the bottom, the total depth being 6.5 m. It fills at a constant slow rate between eruptions which occur at alternating intervals of 2 and 4 hours. An eruption consists of a succession, sometimes more than 300, of detonating explosions, a few rising to a height of 10 m. Eruption appears to take place when relatively light superheated water at the bottom of the hourglass, 6.5 m down, becomes unstable and rises to the top where it flashes into steam.

Bottom and top temperatures are plotted through several eruption cycles of Narcissus in Fig. 8. The eruption takes place when the water in the bottom chamber, for a height of about 2 m, reaches a temperature of 105°C , 12°C above the ambient boiling point for a hydrostatic head of 6.5 m. During the long 4 hour interval, the water overturns a few times: the top is suddenly heated and the bottom cooled. Three such overturnings are discernible in Fig. 8 between the second and third eruptions. An eruption erases all temperature and density differences and the water

recedes to start a new cycle.

The eruption of a columnar geyser is a much different event. The water is stored between eruptions in a fairly narrow tube extending down a few to hundreds of meters. Circulation is essentially prevented by the small diameter of the tube so that before an eruption most of the water in it can become superheated with respect to ambient atmospheric pressure without the temperature at any position in the column exceeding the boiling point of water corresponding to that depth. The water at some particular depth will eventually exceed that boiling point and a steam bubble will form. At first these bubbles collapse in the cooler water above, but later they lower the hydrostatic head because of the large volume they occupy. Lowering the head accelerates steam formation and soon the whole tube cataclysmically empties itself out as a powerful, frequently spectacular, jet of steam and hot water, usually playing for several minutes and often to heights of several tens of meters. Old Faithful Geyser, Yellowstone, is shown in eruption in Figs. 9 and 10. The water (Fig. 10) is ejected intermittently in rapid stacc^ato, propelled by a series of steam explosions. The jetting is followed by a steam phase which develops as waters begin to refill the hot reservoir tube.

Bunsen's temperature measurements (Fig. 11) made down

in the Great Geysir, Iceland, show clearly the heating process. The temperature distribution progresses from Curve 4 in the figure to Curve 2 and it is easy to visualize that Curve 2 would soon penetrate the boiling point curve at about the 10 m level.

Bunsen also commented on the "detonations" preceding an eruption. Recent seismic recordings made at a number of geysers have shown that each has its own characteristic temporal pattern of "detonations" or implosions, its own seismic signature (Nogoshi and Motoya, 1962; Rinehart, 1965, 1968a, 1968b; Nicholls and Rinehart, 1967). At Old Faithful, the implosions begin shortly after an eruption (Fig. 12) and continue at a more or less constant rate to nearly the time of the next eruption as illustrated in Fig. 13.

Perhaps the most definitive measurements illustrating the workings of a classical columnar geyser were ones made down in Crump, a geysering drilled well in southeastern Oregon (Rinehart, 1970b). Geysering is initiated close to the 7 m level when the boiling point curve is penetrated by superheated water. Curve 1, Fig. 15, is the temperature-depth profile an hour or so after an eruption at about the time the tube is filled. Curve 2, the temperature-depth profile some eight or nine hours later just before an eruption, indicates the movement of the superheated water which results in the formation

of a series of steam bubbles (Bunsen, 1848; Nekhoroshev, 1959; White, 1967, 1968; Geis, 1968; Fournier, 1969).

There are many theories explaining geyser action and numerous experimental model studies have demonstrated that geysering can be precipitated and maintained in a wide variety of ways. The workable model of Fig. 1 is representative of these attempts. The earliest theories were those of Mackenzie (1842) and Krug von Nidda (1837) which postulated large cavities in which trapped steam built up pressure sufficient to throw the water out of the geyser reservoir. Much later, Thorkelsson (1928, 1930) was a strong advocate of the importance of gases, nitrogen, argon, and methane, in displacing water to reduce the hydrostatic head.

Temperature measurements starting with Bunsen (1848) (Fig. 11) and recent seismic measurements have firmly established, however, that it is not necessary to postulate any more complicated processes than those described in the beginning of this section to explain the action of many simple fountain and columnar geysers. There are, of course, a large number of geysers whose plumbing systems have varying degrees of complexity. The nature of their structurally intricate systems of passageways and subterranean openings that have a definite pattern of filling and emptying both steam and water are more often a matter of conjecture than explanation. There

are also a few cold water geysers, to be described later, whose operation certainly depends on the evolution of gas.

Surface features of a geyser

The most conspicuous surface features of geyser basins are the raised cones of siliceous sinter forming the nozzles through which the large columnar geysers (Riverside, Old Faithful, Castle, Beehive, Lioness, and Lone Star in Yellowstone) discharge their jets of steam and water during eruptions (Figs. 16 and 17). The size and height of the cone, varying from a half a meter up to five or six meters, is not necessarily indicative of the magnitude of the geyser. White Dome in Yellowstone with its very tall and extremely beautiful cone only spouts a small amount of water through a 10 cm vent. Grand, on the other hand, has essentially no cone although it shoots very large quantities of water. Beehive is nearly perfectly symmetrical; Giant is folded and irregular.

The fountain geysers lie low on the landscape, with their geyserite lined pools. At Narcissus (Fig. 18), the geyserite builds up into beautiful bulbous masses with catch basins filled with water and "geyser eggs", small pebbles coated with many layers of geyserite (Fig. 19). At other geysers and pools, the geyserite deposit has built up lace-like sheets around them (Fig. 20). The geyserite terraces at Great Fountain

(Fig. 21) are spectacular. Although geyserite appears soft and sponge-like, it is in fact very hard and abrasive, colored from browns and pinks to greys and white. There are especially beautiful pools atop Old Faithful's cone (Fig. 22).

Relatively minor changes in drainage patterns or geyser activity often bring about rather radical changes in the appearance of the countryside. Perhaps the most striking is the encroachment of sinter over the forests when changing drainage patterns, new springs or geysers cause the trees to take up water heavy with silica. The water evaporates and the silica deposited in the tree cells causes petrification. A photograph of such a devastated forest is reproduced in Fig. 23.

The reservoir

Knowledge of the precise natures of geyser reservoirs is very limited simply because they reside mostly out of view underground. Probings to any appreciable depth are difficult because of internal obstructions. Most likely large voids and geyser tubes are effects rather than causes of geyser action (Fournier, 1969). No cavern has ever been penetrated during the limited drilling that has been done. Visual aspects of the play of the geyser, temperature soundings, and recorded seismic signatures are perhaps the best clues to the nature

of the reservoir. These suggest that there is a complex network of two systems of narrow channels, one system feeding the bulk of the water to the geyser reservoir and the other system feeding a much smaller quantity of extremely hot water that has come up from great depths. The reservoir itself is a compact, well defined cavity or an interconnected array of cavities, the walls of which are, for the most part, lined with an impervious layer of siliceous sinter or geyserite that has been deposited by the geyser waters. During an eruption, the waters in the reservoir may be merely agitated, partially erupted, or totally emptied, making it difficult to estimate the capacity of the reservoir.

One can conjure up a reservoir system to fit any type of eruption. Six generic types which can account for most geyser action are illustrated in cross section in Fig. 24.

Riverside, Old Faithful, and Beehive which play a sustained jet to considerable height at more or less regular intervals probably have a single standpipe, Type A in the figure. The eruptive action is essentially that described for a typical columnar geyser, each eruption either nearly or completely emptying the pipe. For the larger geysers, the standpipe is probably a few hundred meters long. Old Faithful has been probed to a depth of 175 m (Rinehart, 1969a). Assuming that its tube is 0.2 m^2 in cross section, a 250 m long tube could store the approximately 50,000 liters of water ejected during

an eruption. At the opposite extreme, Vixen, a small geyser in Norris Basin, erupts every minute from a pipe only 3 m long. The drilled well Crump is known to be a narrow standpipe, 15 cm in diameter and 35 m in depth (Rinehart, 1970b). During its eruption, occurring on an 8 to 10 hour schedule, it plays to a height of 30 to 40 m for about a minute.

Deep, narrow pools (Type B, Fig. 24) spawn violent, short lived eruptions. They start abruptly, develop rapidly, and empty the pool. The Great Geysir in Iceland (Fig. 25) (Einarsson, 1967), whose central tube is 3 m in diameter and 20 m deep, is the best known of this type but the much smaller Round Geyser in Yellowstone (Fig. 26), 1 m in diameter and 6 m deep, also puts on a good show, playing to a height of 25 m for a minute or so about every 8 hours.

Many columnar geysers do not build cones. The standpipe, surrounded by a slightly raised rim, is in a pool as shown in Fig. 24, Type C. The water level in this pool vacillates; at times, the pool is empty. The eruptive action, however, is that characteristic of a columnar geyser.

The eruption of Great Fountain or Grand Geyser at Yellowstone is a spectacular series of powerful and sustained fan-like jets of steam and water separated by short periods of inactivity several minutes in duration. At Grand, the jet activity is often interrupted as many as twenty times. There

are fewer pauses in the action of Great Fountain but they are longer in duration, sometimes as much as 30 minutes. It takes more than a single underground reservoir to account for this kind of activity; Type D, Fig. 24 is one possible arrangement.

The reservoir of a classic fountain geyser looks something like Type E for Narcissus and Type F for Solitary Geyser. The hourglass cavity of Narcissus is a mere 6.5 m deep. Its eruption consists of spasmodic overturning of superheated water with very little being thrown clear of the pool. Solitary has a deep central tube (it has been probed to 270 m) (Rinehart, 1970a), but its eruptive action is essentially similar to Narcissus.

The water source

In thinking about the waters of geysers, it is important to distinguish clearly between the water that fills the reservoir and that which heats the filled reservoir. Most geysers are basically continuously flowing warm water springs with the flow maintained at a more or less constant rate, but varying from geyser to geyser. When a reservoir is either partially or totally emptied by an eruption, it then refills until it erupts again. Some geysers overflow for a considerable length of time before erupting. Riverside, for example, which has a 6 hour interval between eruptions, takes about

4½ hours to refill and then overflows for about 1½ hours preceding the eruption. In other geysers, the overflow vent seems to be hidden underground. This may be probably so with Old Faithful.

The water that flows into the reservoir is mostly local ground water that has not circulated to great depth. Many of the geysers in the Upper Basin in Yellowstone are situated along the Firehole River and fill their reservoirs with water from the river. Other geysers lie in heavily saturated catch basins and drainage areas.

The heat source

Heat is supplied to a geyser by the injection of hot water or steam directly into the reservoir of warm water. This injected hot water is primarily trapped meteoric water which, after falling, has followed a long circuitous path for a few kilometers down through heavily fractured and altered rock where it is heated and then convected back to the surface. It is possible that some of this injected water is magmatic but this has not been demonstrated. Most investigators agree that if there is magmatic water present, it constitutes less than 5 percent of the total (White, 1967).

Deep down temperature measurements are the most definitive indicators that the injections are intermittent and sporadic.

Fig. 27 plots temperature as a function of time for the 170 m level of Solitary Geyser. The temperature of the injected water, about 170°C , is not especially high, certainly well below the boiling point of about 230°C for a hydrostatic head of 270 m. Water of this temperature must rise toward the surface before it can be effective in precipitating an eruption.

The positions within the respective reservoirs of the cracks and fissures can also be indicated by the temperature measurements. The channels through which the hot water enters vary from geyser to geyser and hot spring to hot spring. They often lie near the bottom of the reservoir, as suggested in Fig. 24, but they may also be anywhere along the sides.

The escape of subterranean hot water and steam can be noticed all over Yellowstone (Fig. 28). At certain places, the ground literally steams, at other places such as Beryl Springs, steam gushes forth from an orifice, boiling water during the wet season and forming a dry steam jet during the dry season.

The total contribution of the deeper, penetrating, hotter waters to the waters of the geyser is not known and there appears to be no ready way of determining it. The mean surface waters are undoubtedly quite warm when they enter the reservoir, having been heated during passage through

the warm ground. A great deal of additional heat would not be required to make the geyser go critical. Perhaps not more than 20 percent of the water expelled during an eruption has penetrated deeply in the earth.

Eruption patterns

Some geysers erupt quite regularly, others sporadically; some geysers are active for a while, then become inactive, only to rejuvenate at a later time; new geysers come into being while others fade away. There is a continual change in geyser activity, partly periodic, partly secular, and partly sporadic. But there are also remarkable threads of constancy. The average interval of Old Faithful has stayed steady at a little over 65 minutes for more than 100 years, although individual intervals between eruptions vary by a factor of three, 30 to 90 minutes, and the yearly average fluctuates from year to year (Fix, 1949; Rinehart, 1969b). Plume, a small columnar geyser in the Upper Geyser Basin, erupts regularly to within a few seconds on a 28 minute schedule. An approximate 6 hour 15 minute interval for Riverside is nearly as constant.

The intervals between eruptions of some geysers are bimodally distributed. The eruptions of Narcissus, as noted before, follow a fairly regular sequence of alternating 2 and

4 hour intervals. Measurements indicate that the rate of influx of the ground water filling its basin is essentially constant but the eruption terminating a short interval occurs before the basin is filled whereas water runs over the brim for a half hour or so before the 4 hour interval is concluded. After a long interval, the new water begins to boil immediately upon entering the basin; after a short interval, the new water is quiescent. This marked difference in behavior suggests that the basin walls retain the heat taken up when the water is stored during a long interval. The porosity of the geyserite basin walls is high so that a relatively large amount of heat can be stored in the form of hot water filling the interstices.

That preheating of the geyser basin during the long intervals leads to bimodality in eruption interval is evident too in the behavior of the drilled geysering well Crump which is lined with steel casing to a depth of 12 m, below which it is unlined (Rinehart, 1970b). The main eruptions occur at 8 to 10 hour intervals with each main eruption being followed about 25 minutes later by a somewhat lesser eruption. Water fills the tube almost immediately after an eruption, the rate of influx being essentially constant. The high conductivity of the steel casing permits its stored heat to be given up quickly to the incoming water.

The intervals between eruptions of Old Faithful are

strongly bimodally distributed (Rinehart, 1969b). A frequency histogram of intervals plotted for a few month period (Fig. 29) shows that the intervals are roughly normally distributed about two modes: the 70 minute mode is about twice as prominent as the 50 minute. The performance schedule is not regular as in the case of Narcissus and Crump. On some days, there is a perfect rhythm of alternating long and short intervals. On other days, all of the intervals are about the same average length, 65 minutes. On still other days, a few shorts will be mingled among a majority of longs.

The lengths of play of Old Faithful, which range from 2 to 5 minutes, are also bimodally distributed and there is a high degree of correlation between length of play and length of the interval which follows. In fact, predictions of eruptions at the Visitors Center are based on this. A short play presages a short interval and a long play, a long interval. Recent movies taken of a number of eruptions of Old Faithful show no perceptible distinctive difference during the first stages between a short and long play. A long play simply continues at a low level of activity longer following the initial surges. From these observations, temperature measurements, and recordings of seismic noise, it can be concluded that the eruptive episode begins at about the same location within the geyser reservoir and in about the same way whether the play turns out short or long. More of the reservoir is

emptied during a long play than a short.

Preheating of the upper portion of the geyser tube could precipitate a short play by bringing the upper regions of the geyser column to a critical point before the lower regions have had an opportunity to become superheated with respect to ambient atmospheric pressure. Upon relief of hydrostatic pressure by the short eruption, water in the lower regions would not boil but simply remain in place to continue heating up. Once a short play has occurred, the water in the lower regions, being already warm, would certainly be expected to participate in the next eruption and produce a long play. This accounts for the fact that short plays almost never follow one another.

It is easy to trigger a geyser eruption artificially. Soap can be put in the reservoir, or a mechanical, sudden lifting of some of the superheated water to the surface will precipitate action. The bubbles produced by soaping lower the hydrostatic head so that if the geyser column is superheated it will very likely cross over the boiling point curve and flash into steam. Physically bringing hot water to the surface by pulling up a can attached to a rope, accomplishes the same thing. As the water flashes into steam, it throws out water, lessening the hydrostatic head, and causing the water to steam conversion to accelerate. Many dead geysers

have been rejuvenated by the simple expedient of lowering the water level in the basin by boring horizontal holes or digging trenches. The heat balance is so delicate that often only a few centimeters change in level is all that is needed to generate an unstable situation.

No seasonal variations in precipitation and temperature have been observed to affect geyser activity although they have been carefully looked for (Marler, 1954). Apparently the deeply circulating waters have a time constant of 2 to 3 years which is much too long for the circulation patterns to respond to.

The parameter that has the strongest regulatory influence on geyser activity is the rate at which the water in its reservoir is heated. Several factors that control the rate of heating and various effects which they produce are discussed in the next section.

Influence of earthquakes, earth tides, and barometric pressure

As early as 1200 AD, Icelandic chroniclers were aware that earthquakes influence geyser activity (Einarsson, 1967). Geothermal areas, which are notably unstable, make an excellent stage for observing their effects. Some geysers are turned on by a severe earthquake; others are turned off, in both cases responding to the build up and release of strain preceding

and following an earthquake. The 7.1 Hebgen Lake earthquake of August 17, 1959, provided a rare opportunity to see what effects a large, nearby earthquake would have on Yellowstone geothermal areas. These effects have been extensively described (U.S. Geol. Surv., 1964; Marler, 1964b).

Over the 100 years during which observations have been kept on Old Faithful Geyser, it is seen to have responded to every major local earthquake (Rinehart, 1972a). The recent extensive records makes it possible to examine in detail the response of Old Faithful to the Hebgen Lake earthquake (Fig. 30). In 1956, the interval between eruptions began decreasing steadily and rapidly until the time of the quake three years later; then it started to increase. By the summer of 1960, it had reached 67 minutes, a much higher period than the previous 64 minute average for 1950 to 1956 (Rinehart and Murphy, 1969).

The upper curve in Fig. 30 depicts measurements that Russian scientists made on the radon content of the thermal waters of the Tashkent mineral water basin during the period 1956 through 1967, prior and subsequent to the large earthquakes of April 26, 1966 and March 23, 1967 (both intensity VII) (Ulumov and Mavashev, 1967). Again it is evident that an area can respond to build up and release of strains associated with earthquake activity. The water whose radon

content was measured was taken from a deep borehole near the epicenter zone of the earthquakes at a depth of 1300 to 2400 m. About 2 or 3 years prior to the 1966 earthquake, the radon content began to increase, nearly doubling just before the quake occurred, and at the time of the quake, it fell sharply, falling again and again with each large aftershock. On March 14, 1967, the radon content increased sharply from its normal value of 1.7 to 3.2 Mache units, remaining at this level for a week. Following the second large earthquake, the radon content returned to normal after about one week. The time scale of the changes at Tashkent and that at Old Faithful are substantially the same.

The natures of hydro and hydrothermal systems are reasonably well understood in a general way. In a geothermal area such as Yellowstone, the parental heat source is extensive as is the water source in the Tashkent mineral water basin. It seems reasonable to infer that the increasing radon efflux and increased heat flow which would shorten geyser intervals, could result from similar rock deformation and fracture patterns. Under increasing stress, additional micro fracturing is initiated which forms additional passageways, and existing passageways would be modified so that circulation rates and patterns change. The readjustment following a catastrophic earthquake or the plastic flow produced when

earth strain becomes large would tend to consolidate the earth mass and constrict the fissures.

The strains associated with earthquakes, while small, of the order of 10^{-7} or 10^{-8} , appear to be very effective in producing detectable changes in geyser performance, indicating that convective circulation within a geothermal area is extremely sensitive to the application of mechanically applied forces.

Earth tidal forces also have a strong regulatory influence on geothermal activity (Rinehart, 1972a, 1972b). These forces arise from the gravitational attraction between the earth, moon, and sun. They cause the ebb and flow of the ocean tides, and in addition, deform the solid part of the earth, producing strains of the order of 10^{-7} which vary in synchronization with variations in the tidal forces. The maximum variation in gravity, about 200 microgals, due to lunar and solar attraction is about one part in 5 million times the acceleration of gravity. Since the earth rotates on its own axis, the moon revolves around the earth, and the earth around the sun, the tidal force is constantly changing. Its magnitude at any one place on the earth, which is readily calculable, depends upon the relative positions of the earth, moon, and sun (Longman, 1959). In general, the variations have the following approximate frequency components: semidiurnal and

diurnal, due to the rotation of the earth on its own axis; fortnightly, due to the moon revolving around the earth; semi-annual, due to the earth revolving around the sun; 8.8 and 18.6 year, due to the inclination of the orbital planes of the earth and moon, about 5 degrees with respect to one another; and 20,999 years. It has been found that the parameter that correlates best with changes in geyser activity is the total variation in gravity due to tidal forces rather than the maximum or minimum value of gravity attained.

Individual geysers respond differently to the various tidal forces. In general, geothermal areas are so mechanically sluggish that the semidiurnal and diurnal components are filtered out. For example, the performance of Riverside Geyser (Fig. 31) is obviously influenced by the fortnightly and semi-annual tidal components, an increase in variation in gravity causing the geyser to erupt more frequently. The high correlation between eruption interval and the variation in earth tidal forces during May and early June and again from late July through August occurs when the fortnightly component associated with new moon and full moon is especially evident. During September and October it is obscured by the semi-annual component. Build up of tectonic stresses preceding two sizable earthquakes, 4.2 and 4.0, occurring in late July overrode the tidal effects during late June and early July.

The 18.6 tidal component which causes the average tidal force to vary by about 10 percent can influence dramatically the action of a geyser (Rinehart, 1972b). The interval between eruptions of Grand Geyser has varied seasonally from 8 to 40 hours, with two periods of dormancy over some 4 decades of observations. During times of high tidal force, around 1930, 1955, and 1970 (see Fig. 32), it erupted 2 to 3 times daily, only to become almost dormant during the years 1943 and 1960 when the tidal force is the lowest.

It is believed that the changes in frequency of eruption are brought about by the forced compression and expansion of the geothermal area under varying tidal force. Such dilatation would affect the flow rate of the hot water into the geyser reservoir.

The third important mechanical force is a regular annual cyclic variation in barometric pressure which ranges from 6 to 10 mm of Hg. (Wahl, 1942). The influence of barometric pressure on geyser performance manifests itself prominently and obviously at Old Faithful (California), Calistoga, Calif. (Fig. 33). High barometric pressure, which occurs in the winter, shortens the interval, and low barometric pressure occurring during summer, lengthens it, the usual range being from approximately 40 to 49 minutes. The 70 day delayed response must be due to the mechanical sluggishness of the basin in which the geyser is located.

Obviously, many other geysers must be affected by tectonic, tidal, and barometric forces but the observational data is usually too fragmentary to warrant meaningful statistical analysis.

Cold water geysers

No discussion of geysers is complete without mention of cold water geysers whose eruptions are triggered and sustained by evolution of nonaqueous gases, commonly carbon dioxide. One such geyser, Crater Hills, a deep elliptical basin 5 by 7 m, exists in Yellowstone near Fishing Bridge (Bloss and Barth, 1949). And there are two drilled wells near Green River, Utah, which erupt regularly and spectacularly.

Crater Hills is an unusual geyser. An eruption, which throws water 1 to 2 m in the air, lasts 30 minutes, followed by a quiet interval of only 2 minutes. In most geysers, the quiet period is much longer than the eruption. The water is strongly acid, pH of 3.9; most geysers have alkaline waters. The eruptions start when the water is low in the basin; most geysers erupt only when their basin is full. There is no drainage, not even during an eruption. And finally, the maximum temperature measured in the middle of violently "boiling" water, was only 73°C, much below the boiling point.

Both of the geysering drilled wells near Green River, Utah, lie in regions where subterranean carbon dioxide and helium are

known to exist in high concentration. The smaller of the two lies in a flat alluvial basin about 30 miles northwest of the town. It was activated about the turn of the century when a 13 cm diameter well was drilled to a depth of 1000 m. The well, though flowing water at a temperature of only about 15°C, began erupting and now throws water to a height of about 50 m, playing for about 5 minutes at intervals of 40 minutes.

Crystal Geyser, the larger, is found on the east bank of the Green River, 5 miles south of the town. The jet issues from a 45 cm diameter steel casing emplaced to a depth of a few meters. Presumably this geyser became active when a geophysical exploration group put down a fairly shallow hole. It erupts on a 5 hour schedule playing a massive and impressive stream of water for 5 to 10 minutes to a height of 60 m (see Fig. 34). Each major eruption is followed 25 minutes later by a minor one which plays for a minute

to a height of about 6 m. The water in the tube before an eruption is also cool, 15°C.

These geysers have not been discussed in the scientific literature. A tenable explanation of their behavior is that carbon dioxide is fed to the water in the well from surrounding geologic formations at a more or less continuous rate. For a while after an eruption, the water dissolves the carbon dioxide, but eventually becomes saturated. The concentration of dissolved carbon dioxide varies along the column, being

higher at the greater depths since its solubility in water increases rapidly with increasing pressure (Marboe, 1949). Finally when the water can take up no more carbon dioxide, gas bubbles rise toward the surface, perhaps coalescing, raising the column of water, and reducing the hydrostatic head. This release of pressure acts as a trigger since the column is at a critical stage with respect to the amount of carbon dioxide it can hold. Additional carbon dioxide is thus released, forming more bubbles, lowering the pressure still further, and precipitating a violent eruption. The agitation accompanying the eruption enhances its volume. It is somewhat analagous to shaking a can of beer.

Concluding comments

A natural geyser is a rare geophysical phenomenon, primarily because a very special set of conditions must obtain before the normal hot spring will start to and continue to erupt periodically. While a whole host of geyser models can be evoked to explain geyser action, measurements in natural geysers and drilled geysering wells show clearly that two mechanisms are primarily operative. Geysers that throw strong sustained jets generally have cylindrical reservoirs and begin to erupt when water at a few meters depth is heated above the boiling point of water corresponding to that depth. The explosive type eruptions characteristic of pool reservoirs are triggered when blobs of superheated water suddenly ascend

to the surface and flash into steam. The spectrum of activity in some of the more complicated geysers ranges from one extreme to the other, often intermixing the two modes. It does not appear necessary to require large steam-filled subterranean cavities to initiate geyser action.

One of the most puzzling aspects of geyser activity has been the great variability in performance. Detailed and extensive analysis of geyser records vis a vis calculations of earth tidal forces, observations of barometric pressure, and examination of earthquake activity have demonstrated that these forces can strongly affect it. Although the forces are small, the convection patterns in a geothermal area are responsive to them, sometimes dramatically so.

There is very little known about the detailed nature of the plumbing systems of individual geysers and the circulatory systems that supply water and heat. More geochemical research appears to be a most promising avenue of study since the dissolved chemicals can reveal the past history of the water.

The current modest efforts to develop geothermal power (Fig. 35) sources are likely at any time to develop into much more substantial efforts (White, 1965; U. S. Bur. of Recl., 1971; Hammond, 1972; Muffler and White, 1972). A geothermal area is a complicated mechanical and thermal system consisting essentially of a large water-saturated soil and

rock mass with dimensions of the order of kilometers and possessing strong temperature gradients. It is important that in the near future research efforts be encouraged toward developing a better understanding of the gross heat and mass transfer in static geothermal basins; describing flow patterns, discharge rates, and surface heat transfer in well defined thermal anomalies; and appreciating the effects of mechanical forces on geothermal phenomena arising from alterations in porosity and permeability distributions due to deformation of the porous matrix. To quote Allen and Day (1935), "... the truth is, hot springs and fumeroles have never been a matter of much consequence in general geological thought", but the situation must and is changing rapidly.

I wish to acknowledge the very great help that the Naturalists of Yellowstone National Park have been. Many of students in the Mechanical Engineering Department at the University of Colorado have made extensive calculations on which my conclusions are based.

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- Fig. 1. Model geyser described by Munby (1902). Diameter of exit, 6mm. Eruption interval, 10 min.
- Fig. 2. Schematic model of geyser basin. Adapted from White (1967).
- Fig. 3. Solubility of SiO_2 as a function of temperature. After Fournier and Rowe (1966).
- Fig. 4. Specific gravity of water as function of temperature.
- Fig. 5. Boiling point of water as function of hydrostatic head. Standard atmospheric pressure.
- Fig. 6. Blob of superheated water flashing into steam during eruption of Solitary Geyser, Yellowstone. Bubble, 1 m across, is still expanding.
- Fig. 7. Fountian geyser, Strokkur, Iceland, in eruption.
- Fig. 8. Temperatures near top and bottom of Narcissus Geyser reservoir, Yellowstone, as function of time. E indicates eruption.
- Fig. 9. Old Faithful, Yellowstone, at height of winter eruption.
- Fig. 10. Close view of Old Faithful in eruption. Warm day. Note intermittency of ejection.
- Fig. 11. Temperature measurements made in the Great Geysir, Iceland (Bunsen, 1848). Curve 1, boiling point curve; curves 2, 3, and 4 are temperatures of the column of water at the respective periods of 10 minutes; 5 hours and 31 minutes; and 23 hours and 13 minutes, before a great eruption.

- Fig. 12. Seismic signals generated at Old Faithful by steam bubble implosions.
- Fig. 13. Cumulative total as function of time of seismic signals of type shown in Fig. 12.
- Fig. 14. An eruption of Crump, a geysering drilled well. Height of jet, 35 m.
- Fig. 15. Down-the-well temperature profiles at the geysering well, Crump. Curve 1, an hour after an eruption; curve 2, just before an eruption. Composite curve made up from a series of readings.
- Fig. 16. Close-up view of geyserite cone, Lone Star, Yellowstone.
- Fig. 17. Steam phase, Castle Geyser, Yellowstone. ASYmmetrical cone about 4 m high.
- Fig. 18. Pillows of geyserite lining pool reservoir of Narcissus Geyser. Seismometer in right background.
- Fig. 19. Geyserite eggs near rim of Narcissus. Largest egg 4 cm across.
- Fig. 20. Lace-like geyserite surrounding hot pool in Upper Geyser Basin. Firehole River in background.
- Fig. 21. Geyserite terraces at Great Fountain, Yellowstone. Steam phase.
- Fig. 22. Geyserite building up in pools atop Old Faithful's cone.
- Fig. 23. Devastated forest in Yellowstone due to changed drainage patterns.

- Fig. 24. Cross sections of generic types of geyser reservoirs.
- Fig. 25. Temperature probings of the pool, Great Geysir, Iceland, when it was quiescent, 1967.
- Fig. 26. Round Geyser, Yellowstone, just after emptying itself. Wire connects seismometers.
- Fig. 27. Temperature as a function of time at a depth of 270 m in Solitary Geyser. E indicates eruptions.
- Fig. 28. Steaming at Lower Geyser Basin, Yellowstone, on cool evening. Firehole River in foreground.
- Fig. 29. Frequency distribution of intervals between eruptions of Old Faithful for summer season, 1965.
- Fig. 30. Lower curve: yearly (summer season) averages of intervals between eruptions of Old Faithful, 1950-1970, preceding and following Hebgen Lake earthquake of August 17, 1959. Upper curve: radon content in ground water at Tashkent, USSR, preceding and following large local earthquakes, April 26, 1966 and March 23, 1967.
- Fig. 31. Interval between eruptions of Riverside Geyser, Yellowstone, as function of time: upper curve, summer season, 1967; lower curve, computed variation in earth tidal force. Times of the phases of the moon are indicated by appropriate symbol; the positions of apogee and perigee are indicated by A and P, respectively.

Fig. 32. Observed temporal variation in frequency of eruption of Grand Geyser, Yellowstone, and computed variation in gravity due to earth tidal forces.

Fig. 33. Upper curve, temporal variation of the interval between eruptions of Old Faithful (California) Geyser; middle curve, barometric pressure; and lower curve, rainfall. The area between the two top curves is shaded to facilitate visual comparison. Numbers directly above the rainfall curves give the total annual rainfall in centimeters.

Fig. 34. Crystal Geyser, Green River, Utah (cold water) in eruption. Pipe from which jet issues is 45 cm in diameter. Jet is 50 m high.

Fig. 35. Cerro Piedra, Mexico, geothermal field under development.

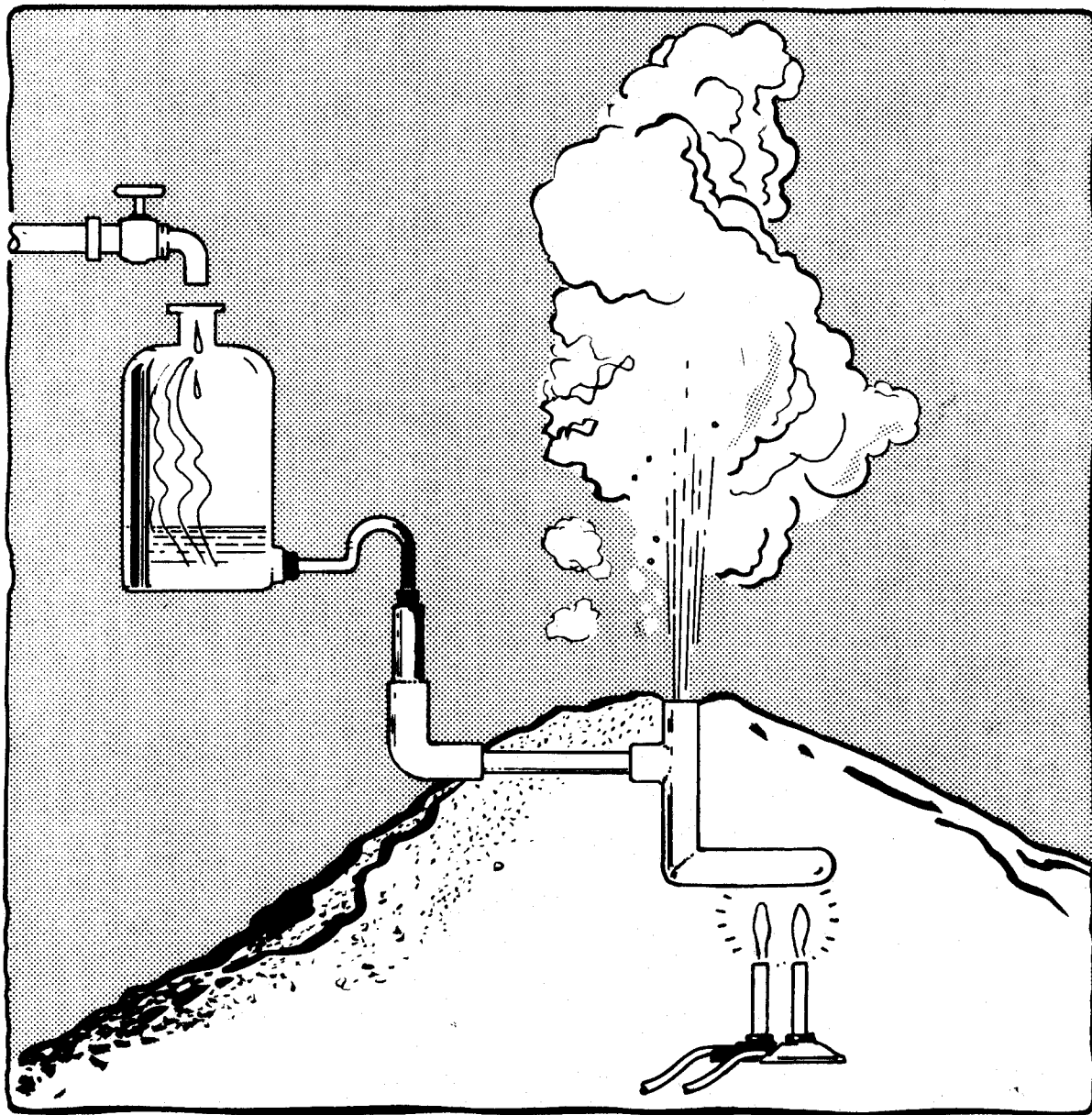
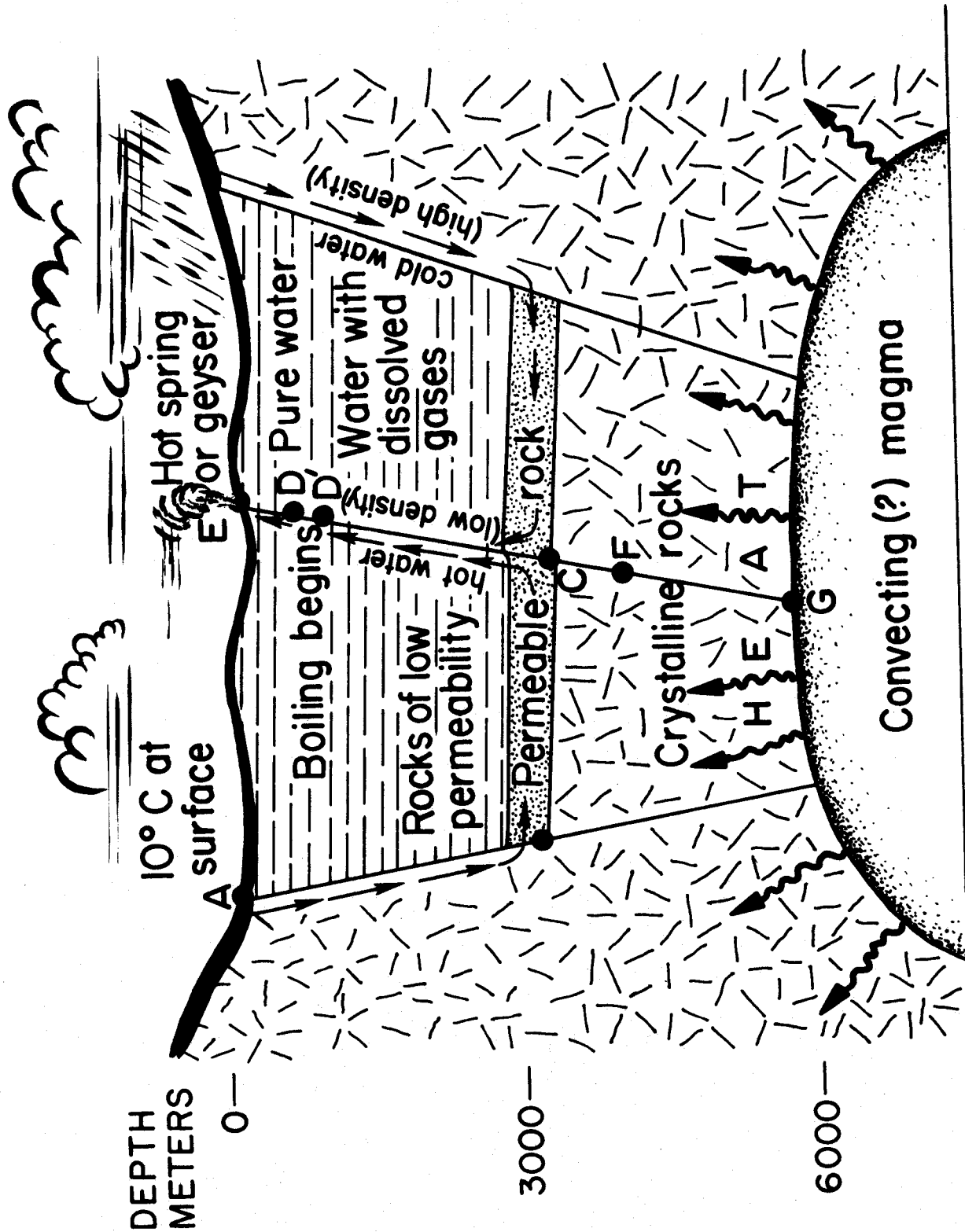
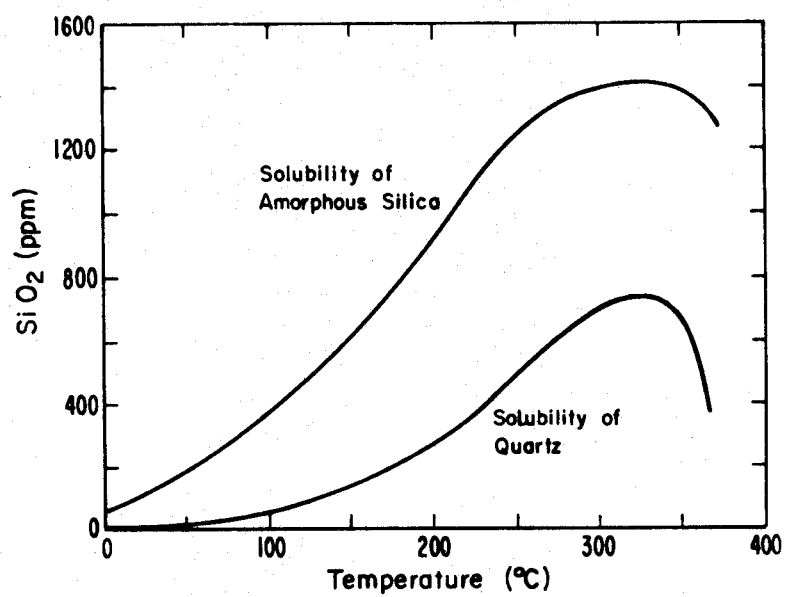
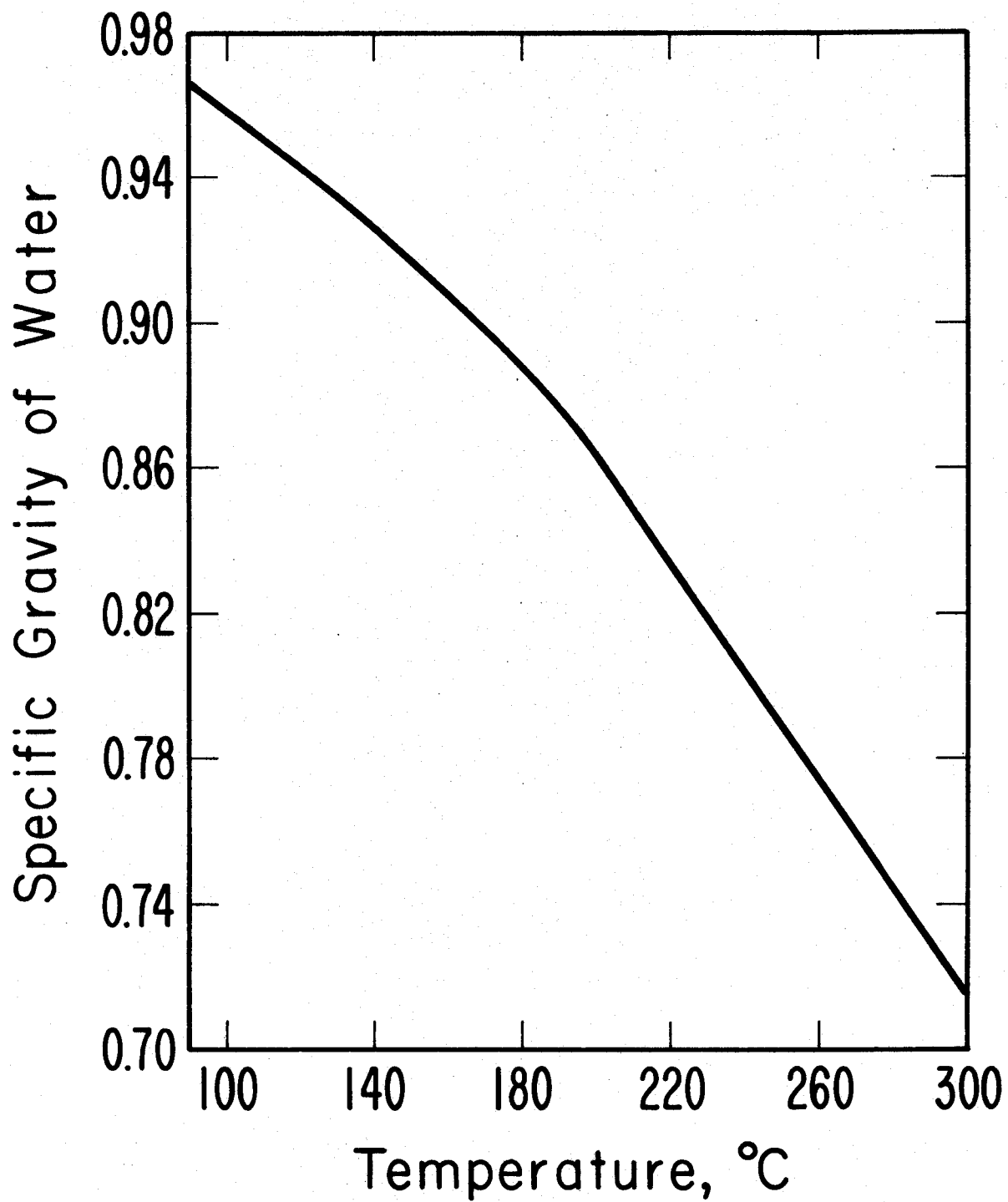
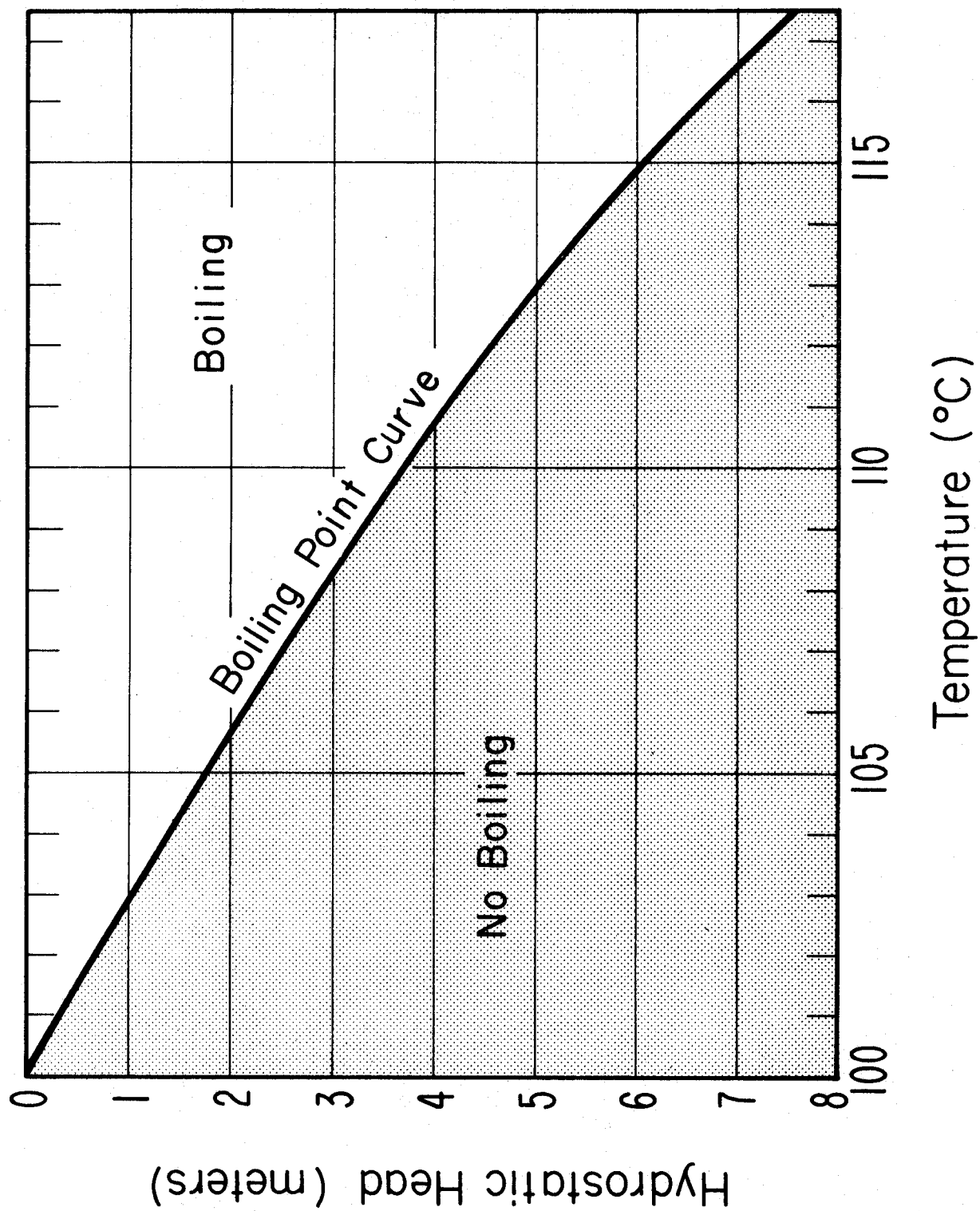


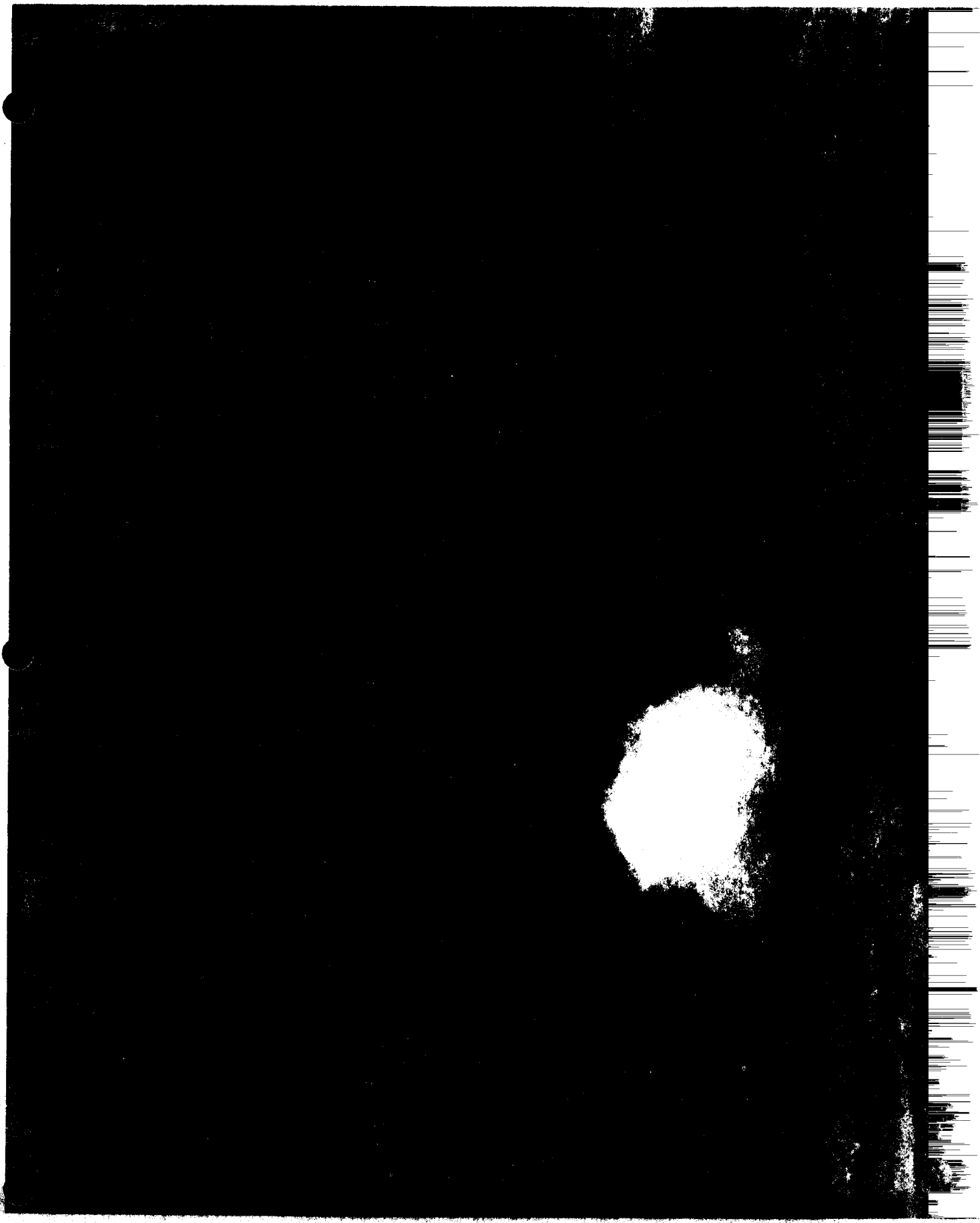
FIG 1 - Rinehart





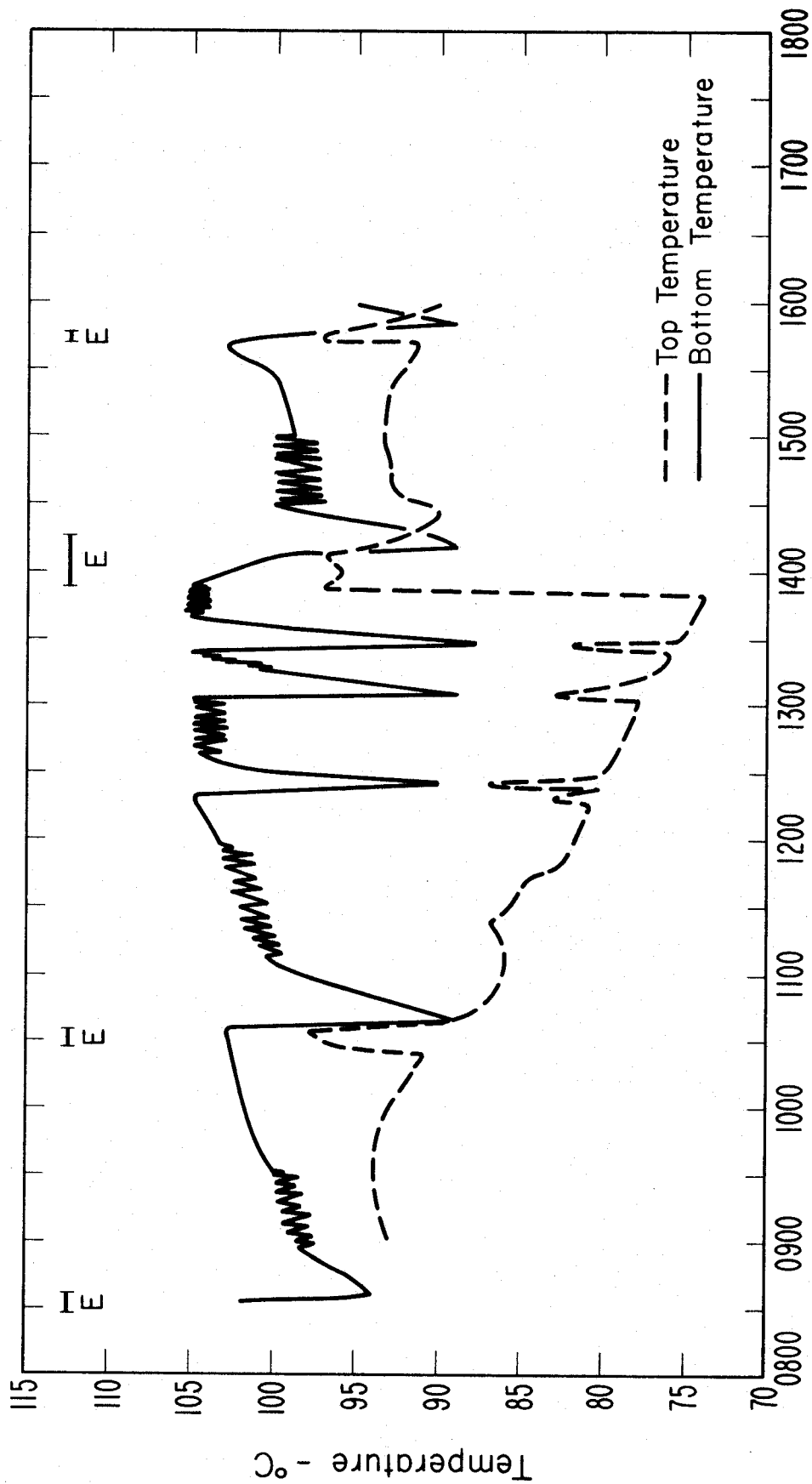








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FIG 4-2 (Rev. 10-68)





FIG 10 - Rnubant

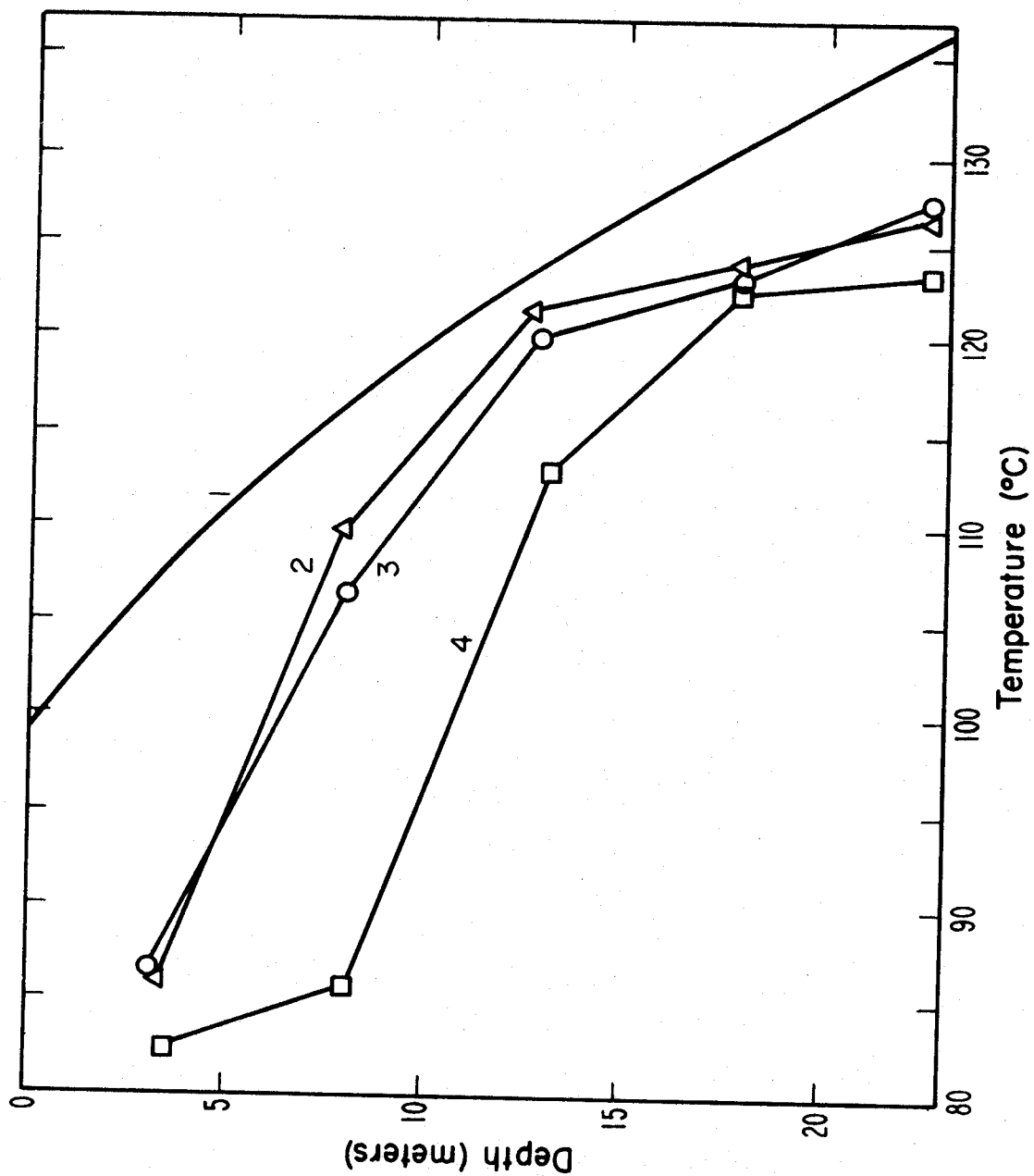
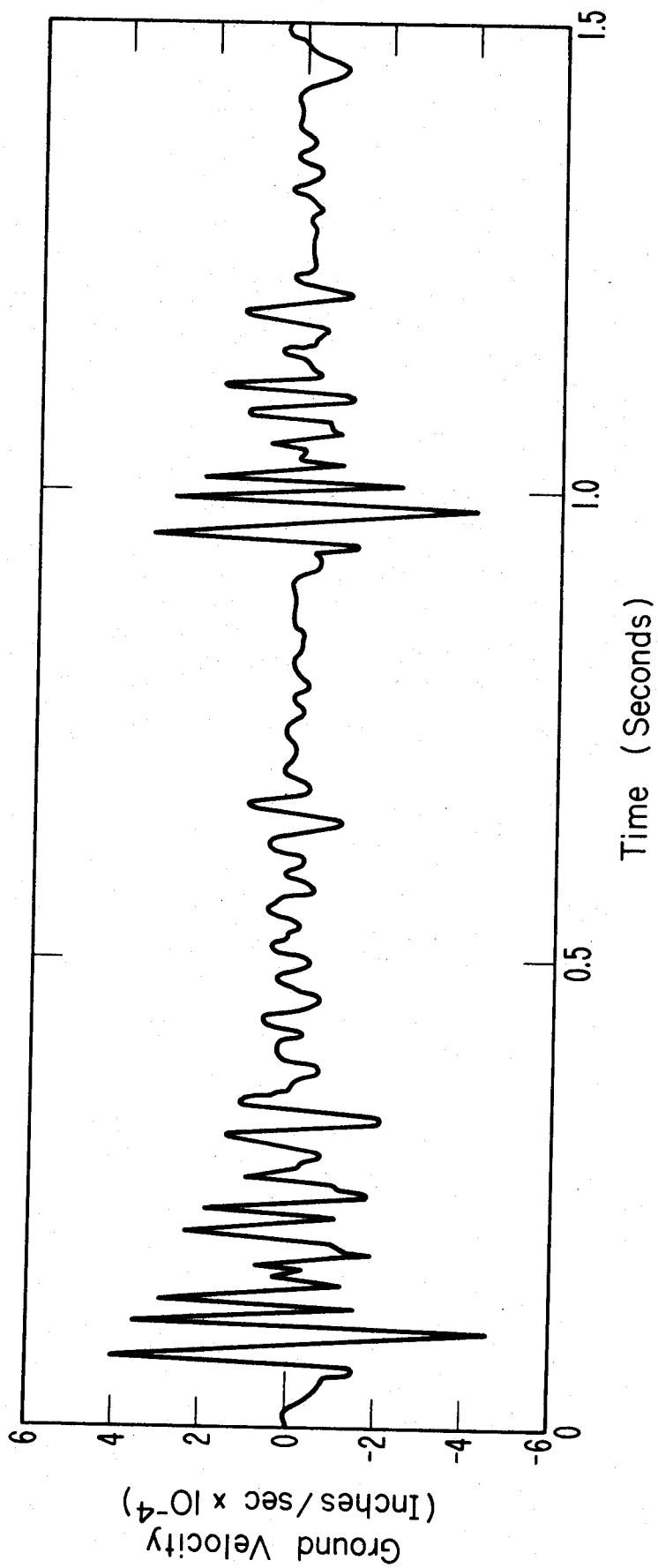
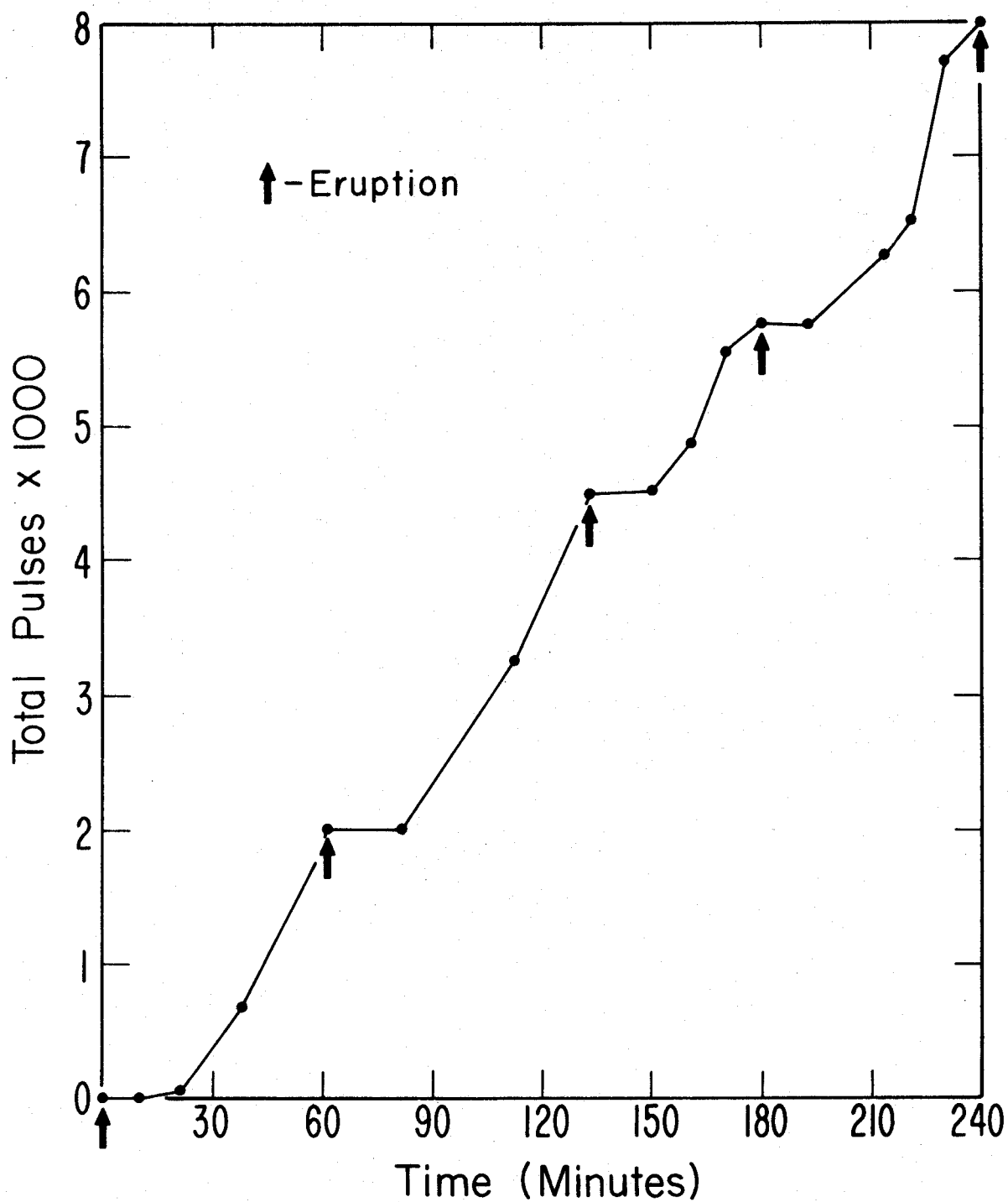
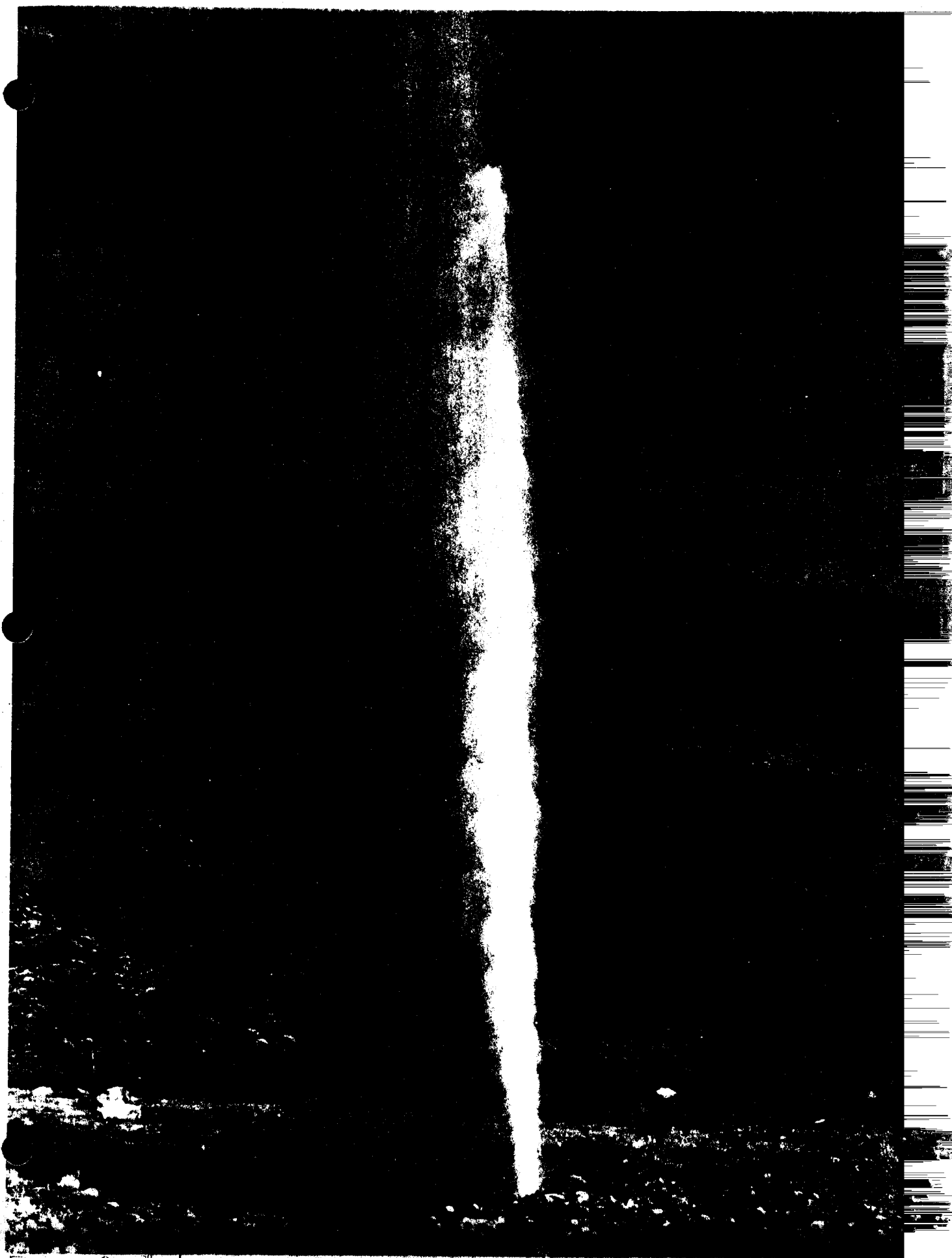
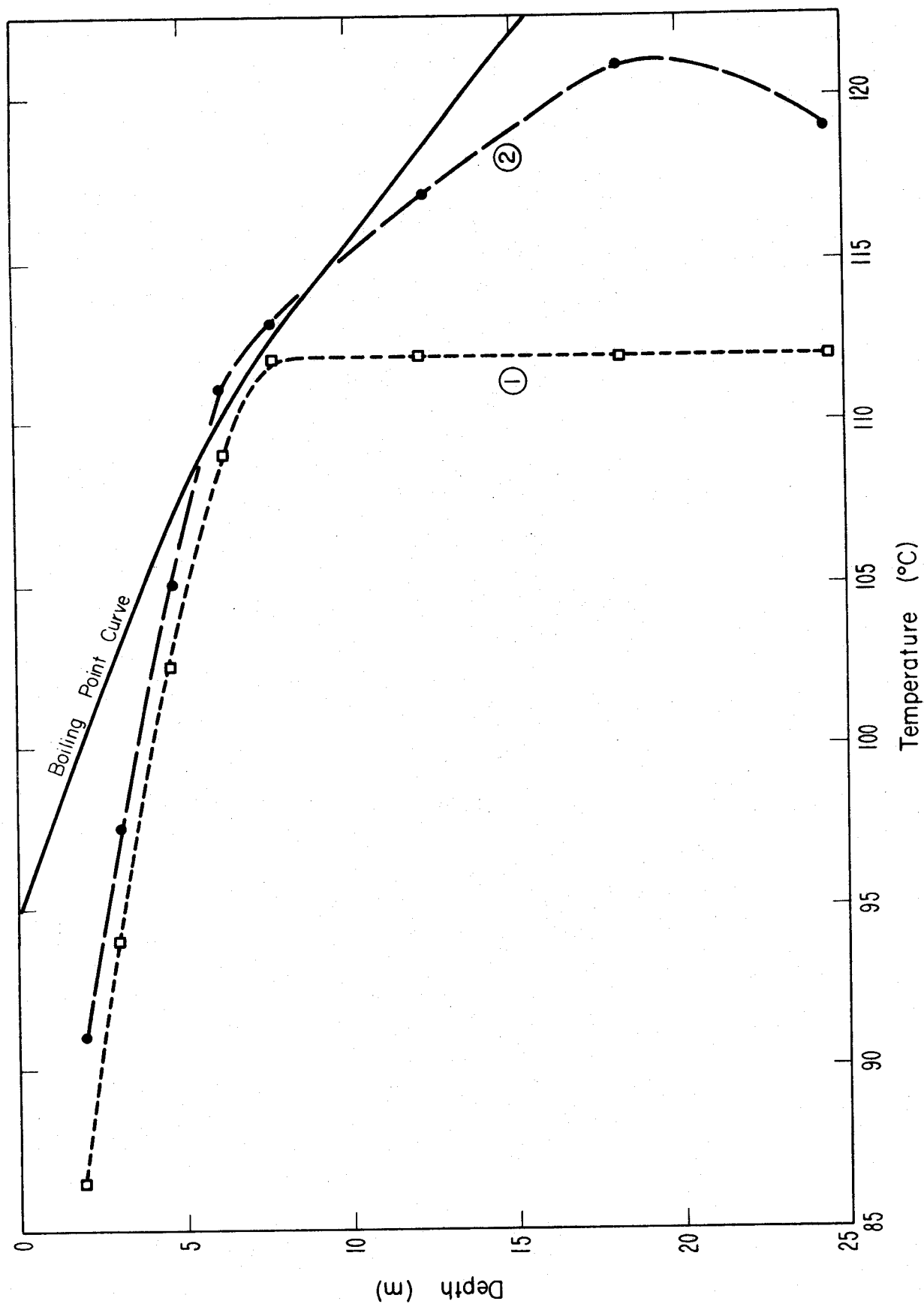


FIG 11 - Pinchart











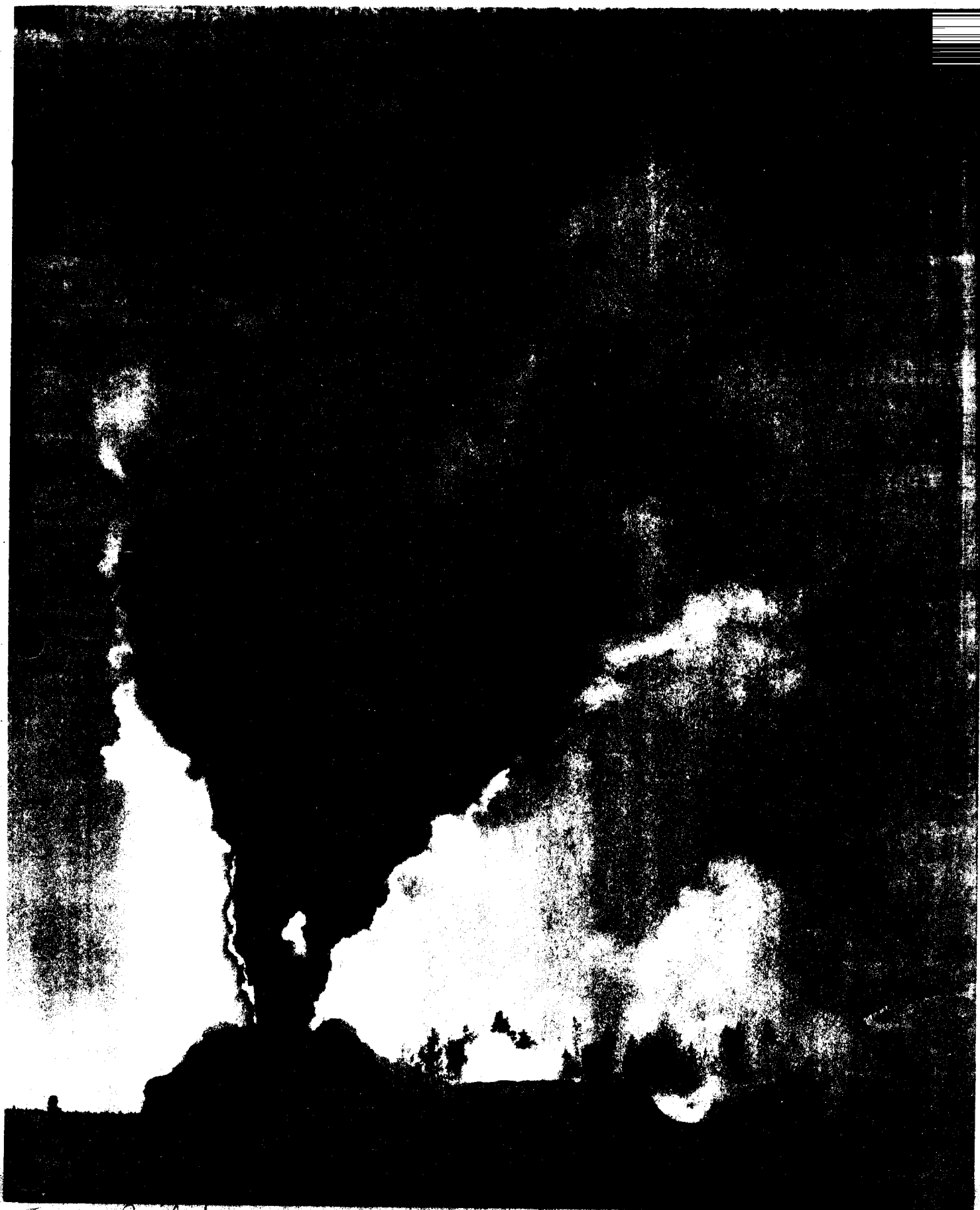
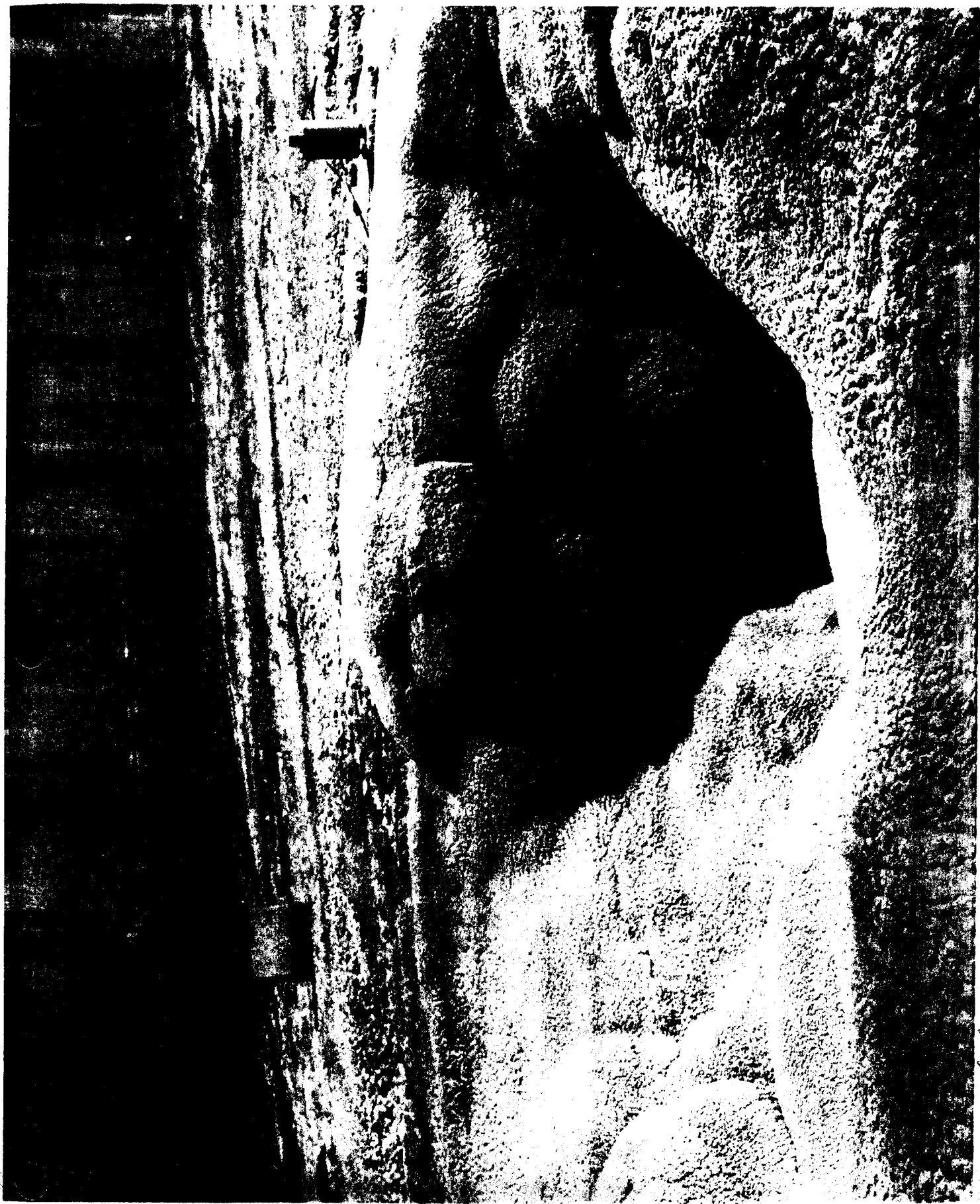


Fig. 1 - Rm. 100



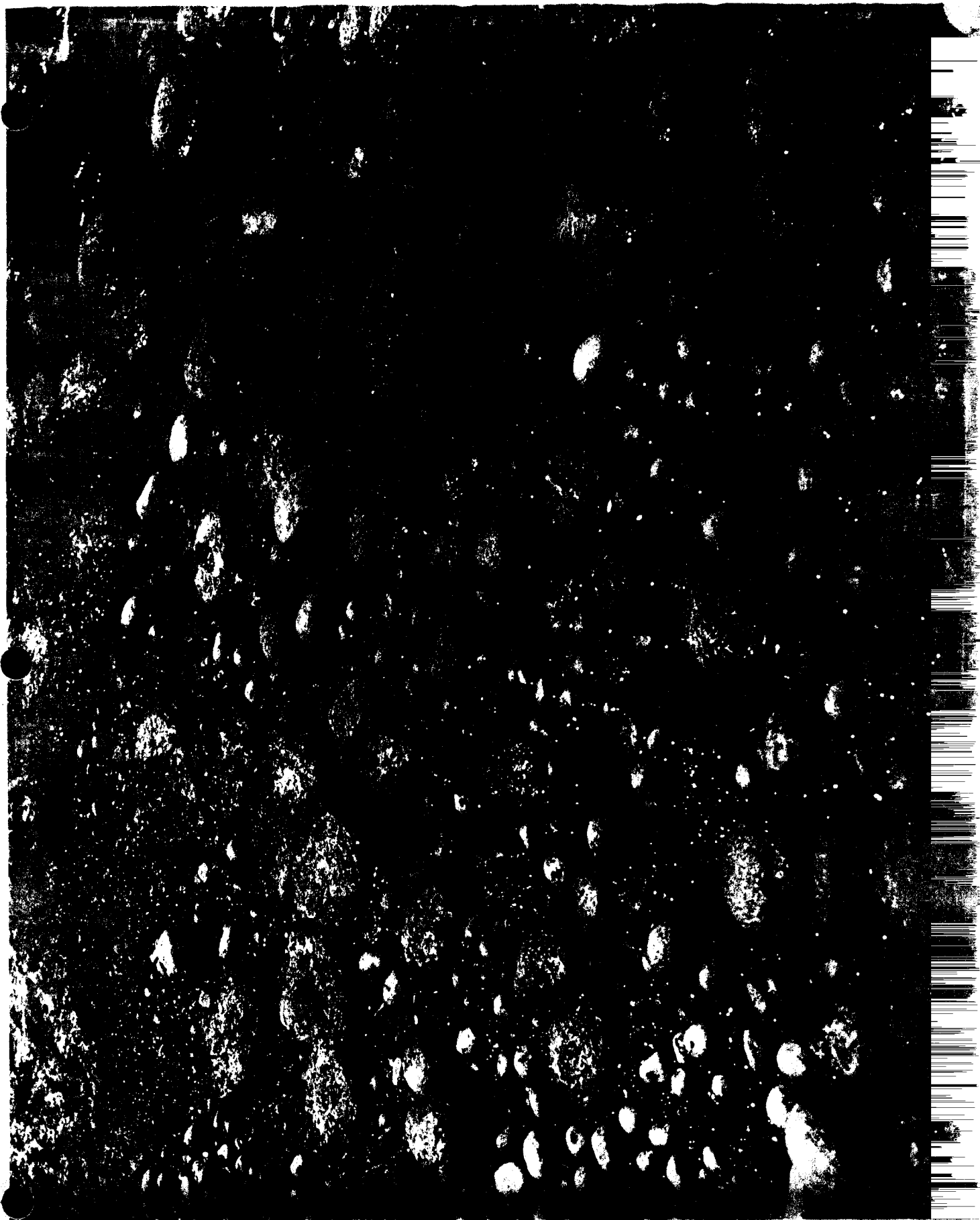
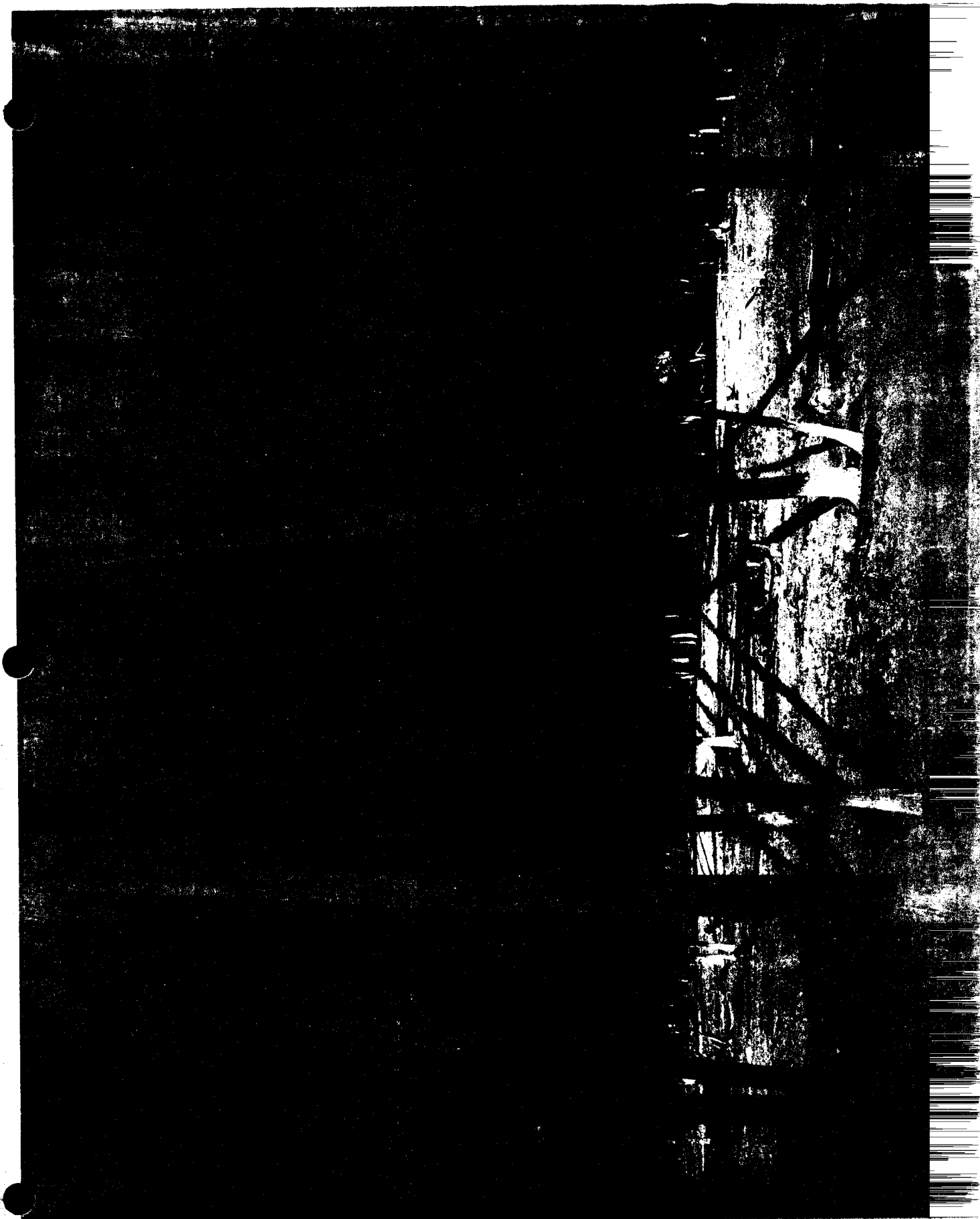


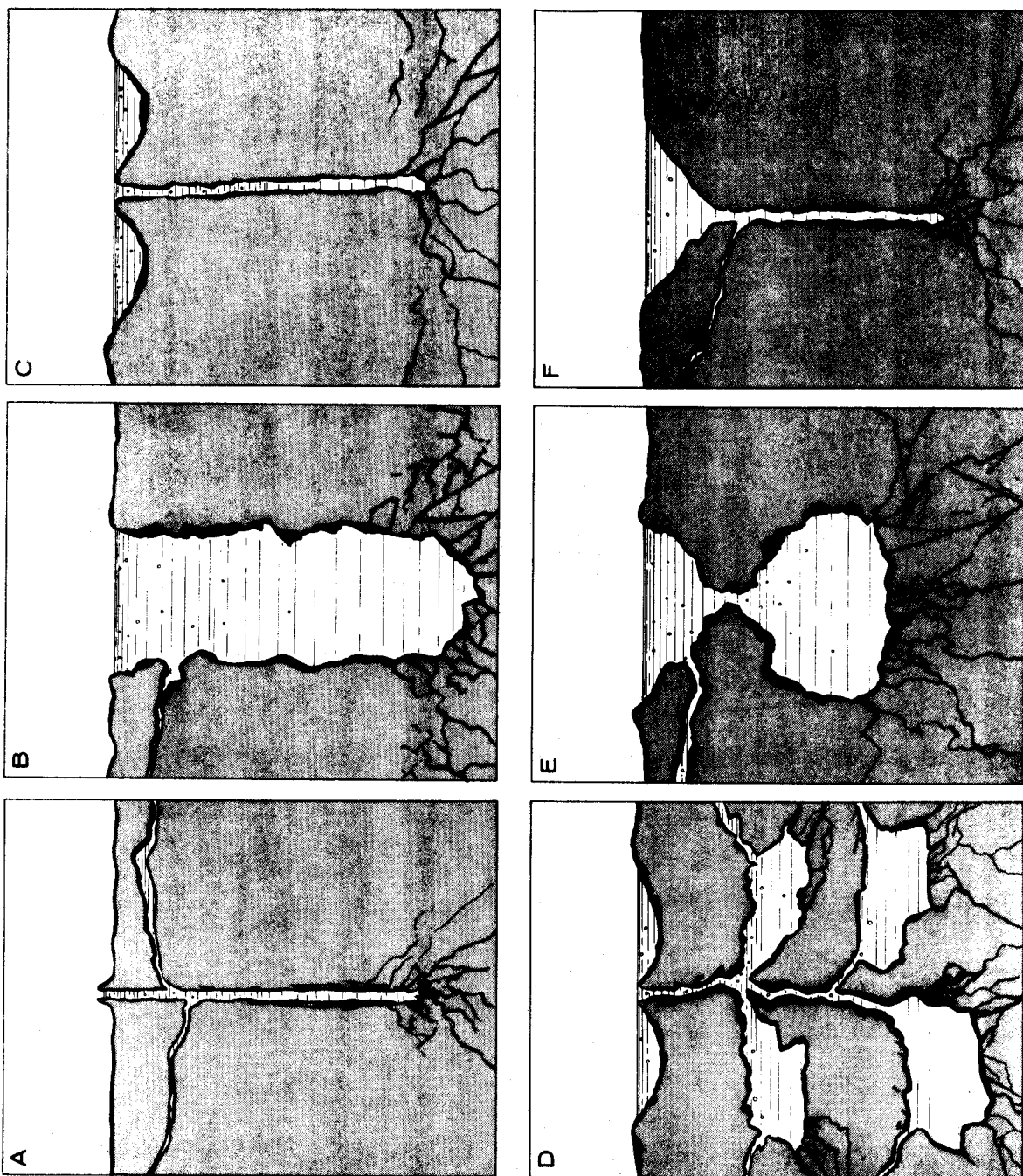




FIG 21 - Rimelent

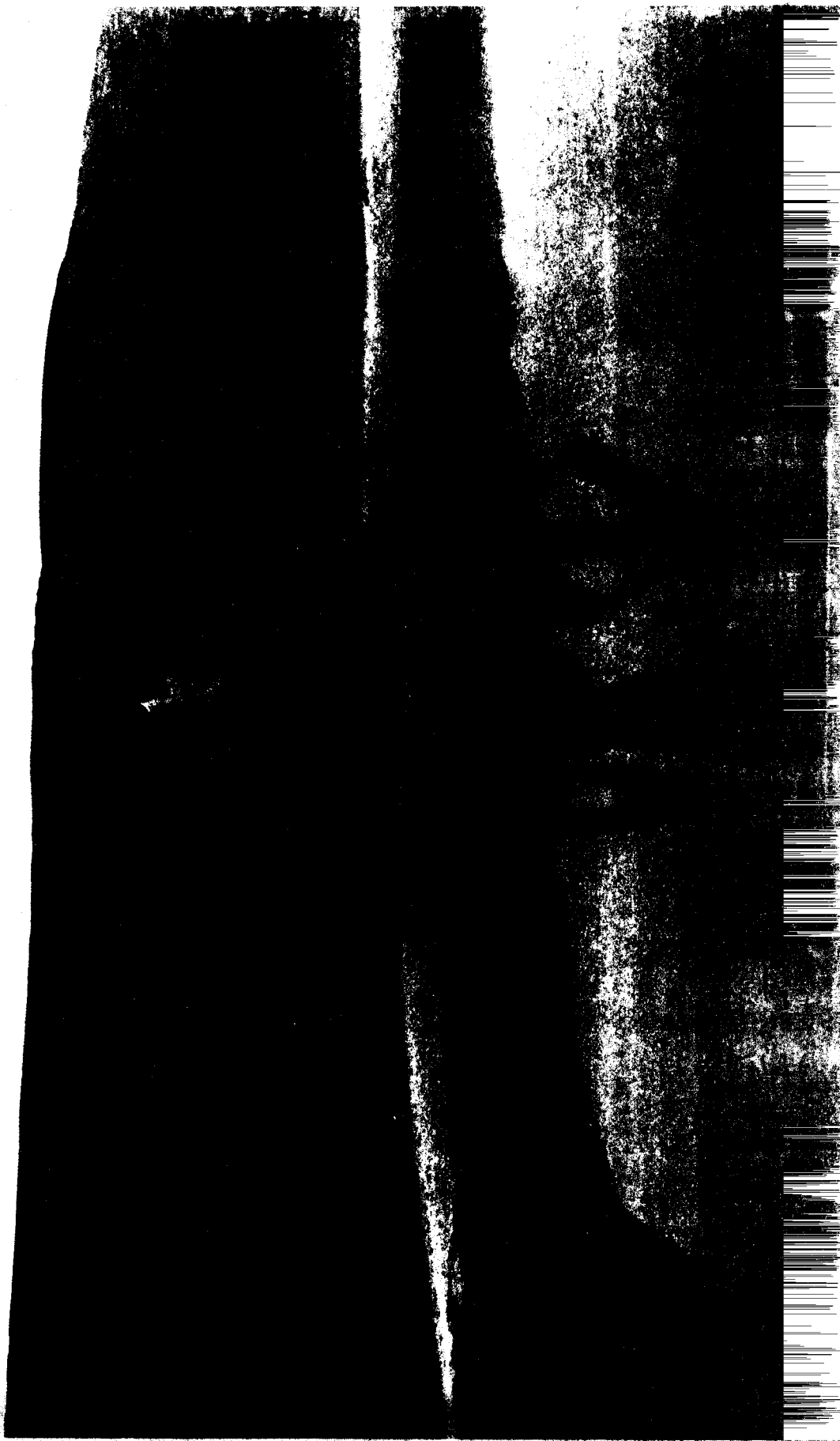




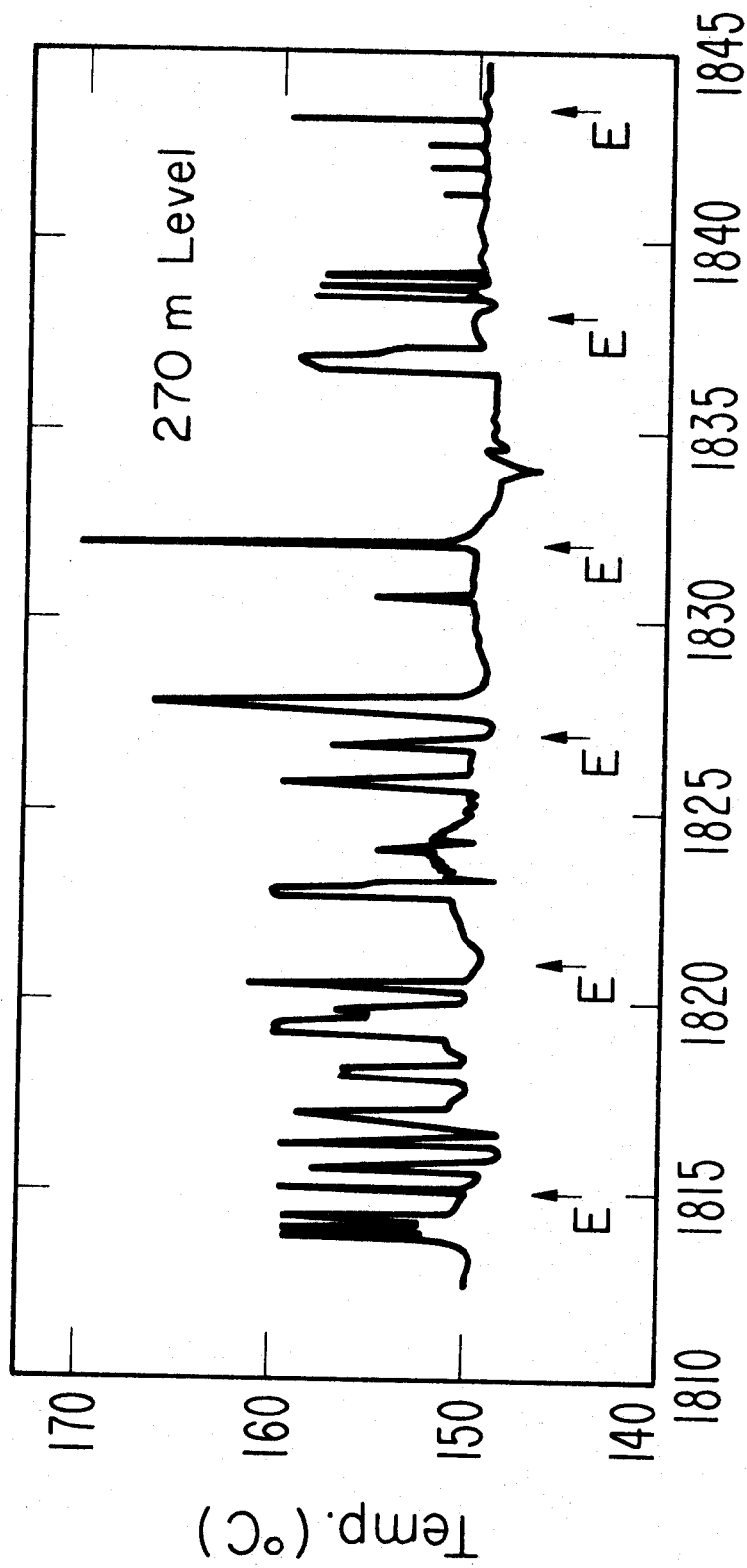


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Figure 2. D. A.



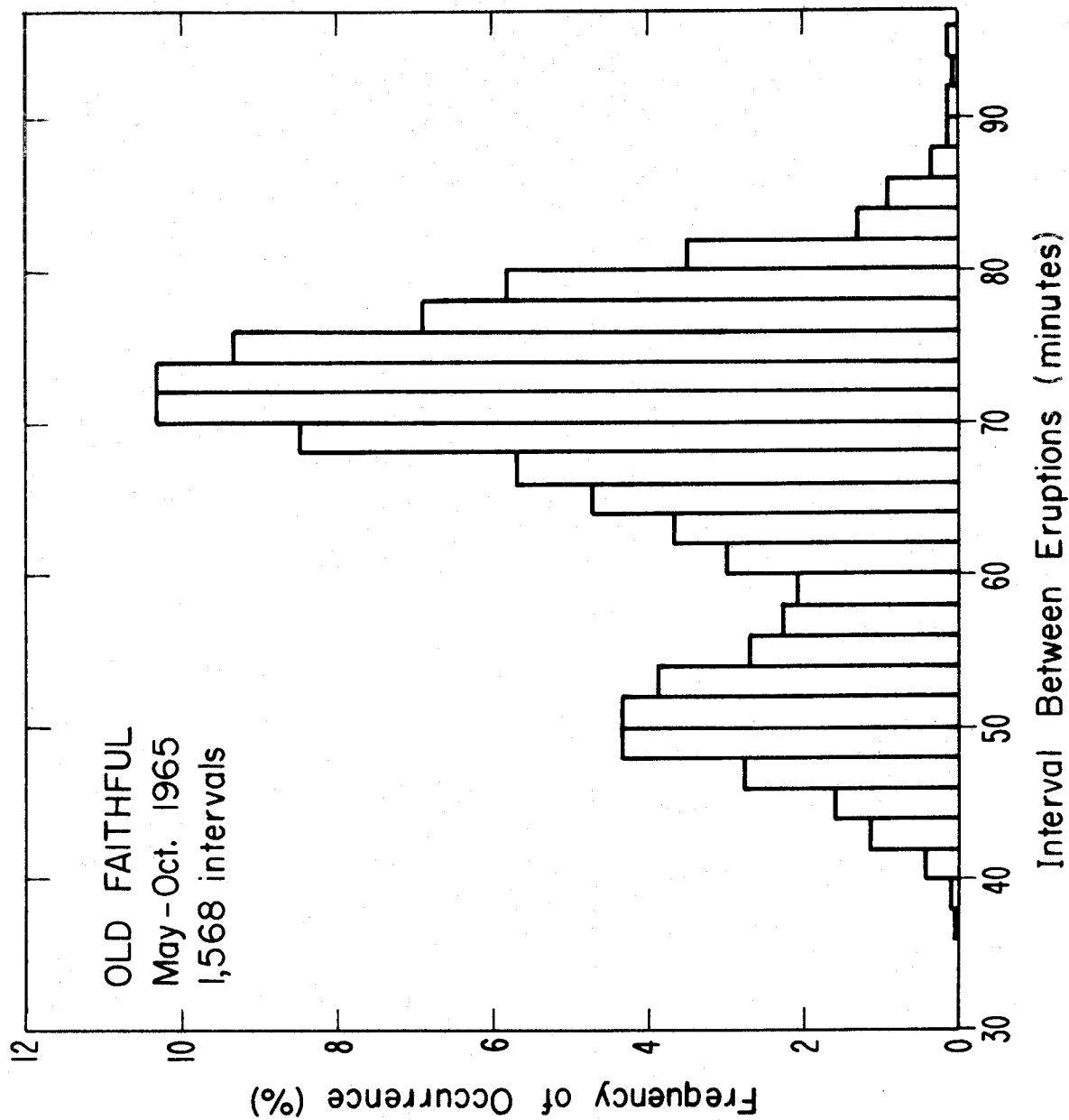


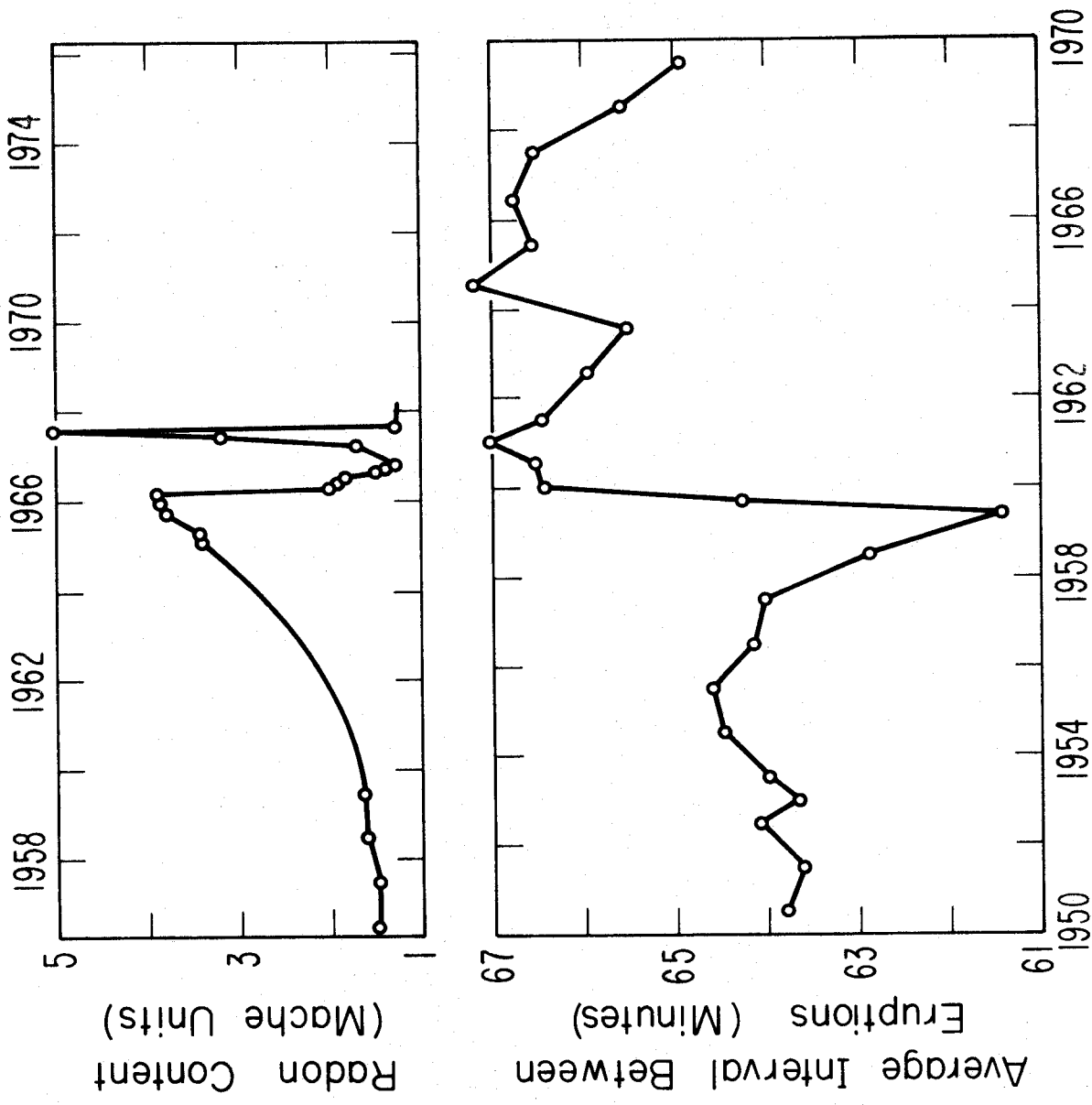


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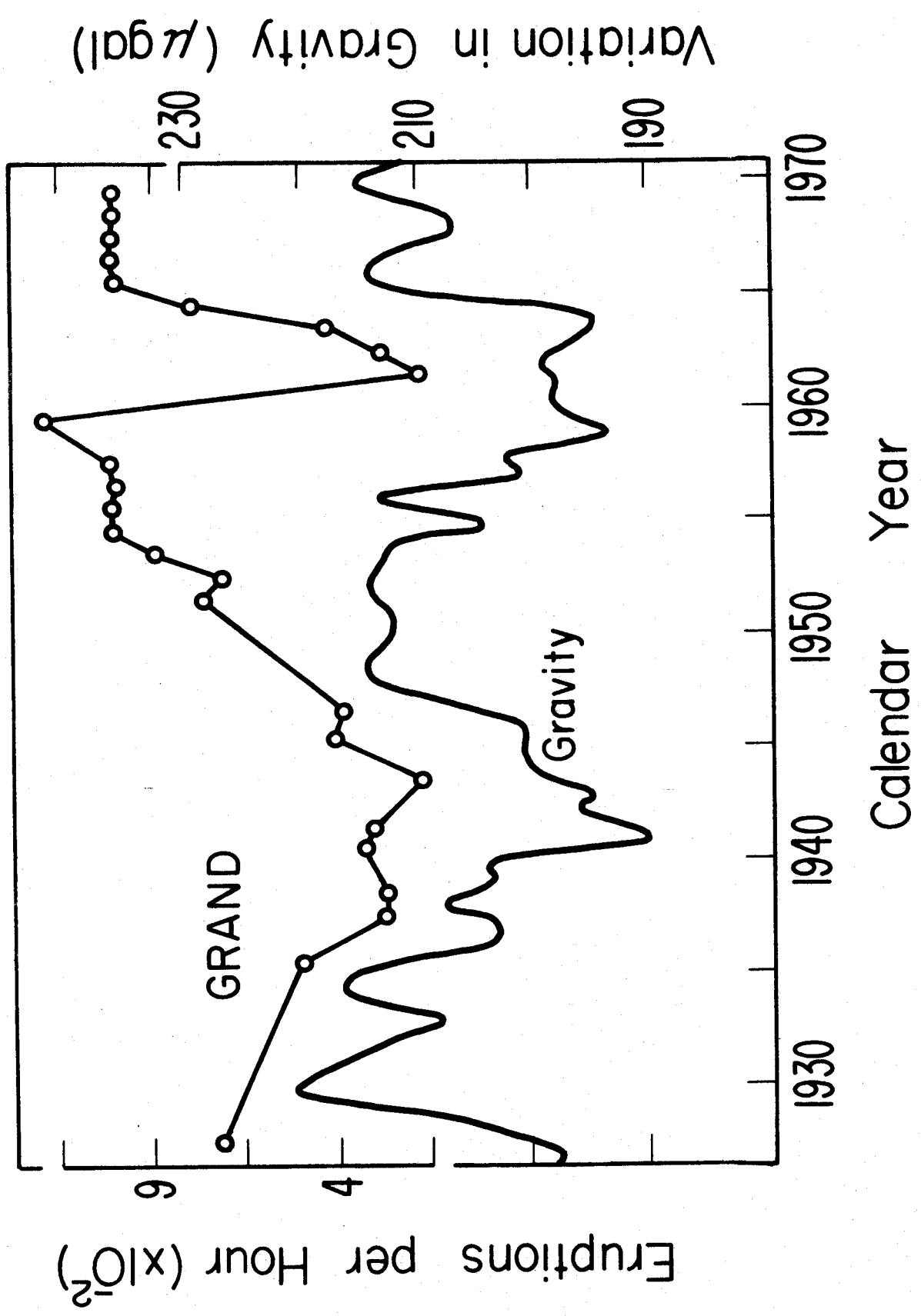


FIG 28 - MICHIGAN









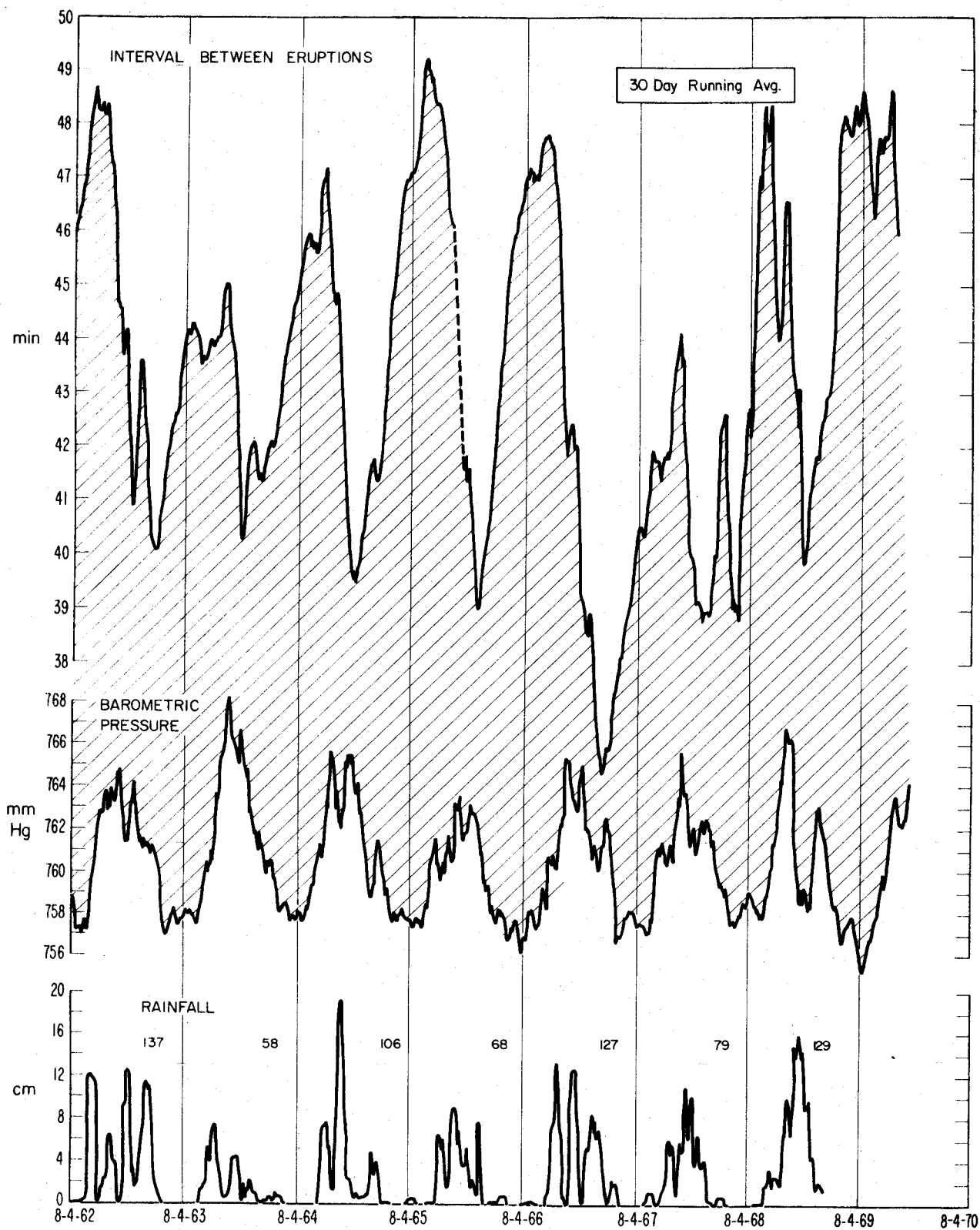


FIG 33, *Kilauea*



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