Mem. Fac. Educ. Ehime Univ.,Nat. Sci., Vol. 7 191～220(1987)

Potholes in Shikoku, Japan, Part Ⅱ. Origin of Potholes and Significance of Pothole Research

Shinji SATO and Tomoko HAYAMI

Department of Geological Sciences,
Faculty of Education, Ehime University,
Bunkyo-cho, Matsuyama City, Ehime 790, Japan

(Received October 11, 1986)

Ⅰ Introduction

As already mentioned in Part Ⅰ, a systematic research on potholes in the Kurokawa River, Ehime Prefecture including famous "Yakama Potholes" was carried out by eight geologists and five geographers in 1982–1983. Results of the research were published as Research Report in Japanese (Yakama Research Association, 1984). In Part Ⅰ, distribution and morphology of potholes in the Kurokawa River and discussions of their hydrodynamics are stated. In this paper (Part Ⅱ), some review and discussions on origin of potholes are stated based on a previous study (SATO and HAYAMI, 1984).

Acknowledgment

The authors would like to express their deep gratitude to the following persons : Dr. Kozo NAGAI, Professor Emeritus of Ehime University, Mr. Ryukichi ITO, Professor Emeritus of Seikei University, Dr. Kagetaka WATANABE, Professor Emeritus of Tsukuba University, and Dr. Hiroshi YAMAUCHI, Professor Emeritus of Ehime University, who taught them hydrodynamics, and also their thanks to Professor Naruhiko KASHIMA, and Dr. Jiro TAKAHASHI of Ehime University for their assistances.

Ⅱ Origin of Pothole

The oldest paper about pothole began with KALM (1742) of Sweden. Since CHARPENTIER (1841) described potholes in upper stream of the Rhone River, France and proposed

"Moulin Theory" of potholes, a glacier hypothesis about origin of pothole continued for nearly a hundred years. ALEXANDER (1932) of U.S.A. presented "Eddy Theory" of potholes based upon a hydraulic experiment, and therefore, the glacier hypothesis about origin of potholes declined. In Japan, the "Eddy theory" is well known, but in Europe and U.S.A. "Cavitation Theory" about origin of potholes has been appreciated recently. In Asia TSCHANG (1958, 1964) mentioned an interpretation about origin of potholes in Taiwan and Hong Kong from many viewpoints. ITOH (1979) published a book, "Pothole Erosion in Japan".

A. Moulin Theory

This is a theory or hypothesis that potholes in eroded areas by recent glaciation, far from recent river system, were formed by glaciation. It is an interpretation that the potholes were eroded by a sort of waterfall which fell through crevice of glacier and reached bedrock (BRÖGGER et REUSCH, 1874 ; UPHAM, 1900 ; GILBERT, 1906 ; MARR, 1926, etc.). Even after an appearance of Eddy Theory, FAEGRI (1952) and others supported this hypothesis.

ELSTON (1917) recognized that some potholes were formed by glacier action and they belonged to "Moulin potholes" or "Giants' Kettles". However, he also said, "because all types of potholes depressions are not to be explained by any one process, it has seemed worth while to attempt a rational classification of these phenomena of the basis of their mode of formation and then to described briefly each of the types." He classified potholes into three classes, and his class A included "Moulin potholes". ELSTON (1918), further said, "An initial hollow in the bedrock is necessary to permit of the primary collection of the sediment and stones that are to be the tools with which the pothole is ground out. Most of the erosion of the holes is apparently accomplished during flood stages." We believe that ELSTON's opinion mentioned above is very important, and we will discuss flood stages in later section.

FULLER (1925) said, "The eastern flank of the Front Range in north central Colorado shows a remarkable series of potholes related to the early Pleistocene glaciation of the region. The potholes are directly linked up with ancient cirques, U-shaped valleys, striae, and perched bowlders in the chain of evidence which indicates that these early Pleistocene glaciers covered 75 to 80% of the region and had many of the characteristics of an ice cap with pendant valley glaciers, fringing well out of the foothills."

FAEGRI (1952) said, "In geological text-books the explanation is generally given that potholes are formed by semi-permanent "moulins" which occur where the glacier breaks over a sharp edge. Consequently there will be a semi-permanent crevasse through which waterfalls more or less vertically down on to the glacier bed. STREIFF-BECKER (1951) contends that potholes are not produced in this manner. The locality is a small, exposed ocean island west of Bergen, Norway, called Kvannholmen, near the very top of which (height 23 m) there is a group of quite good potholes. The one is 3.20 m deep with a diameter of 1 m. It will be seen the location of the potholes is very easily explained by the old theory. In late-glacial times the island was submerged and emerged again."

HOLLINGSWORTH (1951) said, "Would one not be as justified in assuming that a deep pothole demands plunge-pool action as in assuming the elimination of the crevasse-to-plunge-pool idea by postulation of a thickness of several handreds feet of ice? The pothoels on the Maloja Pass to which STREIFF-BECKER (1951) refers are fine examples of deep cylindrically drilled holes. They are situated on the rocky crest of the pass just where crevassing might be intense."

B. Difficulty of Moulin Theory

ALLEN (1982) stated, "There are grave objections to the glacier-moulin interpretation, first voiced by ALEXANDER (1932) and since amplified by ÄNGEBY's studies of potholes (1951) from river rapids, primarily because the potholes found in glaciated areas, either buried or exposed, differ in no essential way from those currently being shaped by streams or arising in laboratory experiments intended to simulate river entrenchment (SHEPHERD, 1972 ; SHEPHERD et SCHUMM, 1974). The other objections, extensively considered by ALEXANDER (1932) and HIGGINS (1957), are that : 1) few of no glacier crevasses are likely to remain stationary for long enough to permit the degree of erosion demanded by the size of most potholes, 2) even if the crevasses were in motion, no one bedrock site is likely to be precisely re-occupied by a series of moulins, and 3) the ice is unlikely to have been so thin that the crevasse would have provided an uniterrupted shaft to bedrock."

STREIFF-BECKER (1951) of Zürich said, "Not all potholes have any connection with glacial action, as was pointed out by Albert HEIM (1885). As we descend a glacier and reach the fine line we find, if the day is hot, that the melted snow and ice gathers into small streams which unite to form larger ones. The water, heated by insolation, melts deep channels in the ice. If the stream reaches a steeper slope where crevasses appear it will naturally flow into one of these (Fig. 1-a) and by devious paths, or under favourable conditions in one leap, reach the glacier bed. It is well known that crevasses always open at approximately the same place in a glacier when it flows over a convex step in its bed. They gape wide open, and close up again as the slope fattens out (Fig. 1-b). When melt water stream (W of Fig. 1-b) enters a crevasse it melts a more or less cylindrical shaft of the up-hill side of the crevasse wall (II of Fig. 1-b). This maintains its shape even after the crevasse has closed up in its course from II to V . At VI the crevasse has become a barely visible scar but the shaft still remains. These shafts are generally known as "moulin" (in French) or "glacier mills". In German the more appropriate term of "shaft" (Schacht) is often used. The subglacial stream runs at high velocity in its confined channel, strikes against a hard bottom moraine in a hollow and sets units of this rotation. This process is exemplified by the smaller stone in Fig. 1-c."

HIGGINS (1957) of California said, "In the early 1930's several writers (DE GEER, 1932 ; ALEXANDER, 1932) began to doubt the moulin hypothesis and by the early 1950's most writers had abandoned it in favor of the view that large potholes are formed by eddy cur-

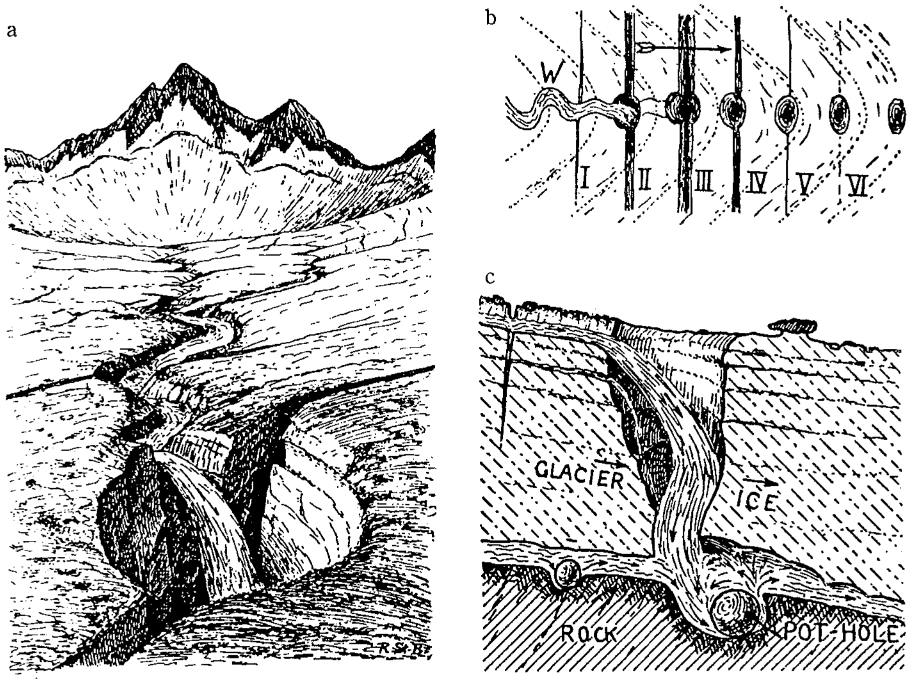

Fig. 1 Explanation of formation of potholes by subglacial stream, after Streiff-Becker (1951, p.489).

rents in sub-aerial or subglacial streams. According to the principle of Uniformitarianism, they suggest formation by running water."

Ångeby (1951) of Lund, Sweden said, "When the stream falls down a vertical ledge it has the opportunity to dig out a plunge pool hole. If the velocity is great (*i.e.* if the waterfall is high) the protecting layer of water, which is held to the rock through adhesion, will be broken and the water itself can produce erosion. Much of the erosion in plunge pools is of the tool-less type. During the last 20 years several big hydroelectric power-plants have been built at the waterfalls on two rivers near Nämforsen, northern Sweden. These waterfalls are thus, dry for the greater part of the year. For the first time, therefore, it is possible to investigate the erosion in these waterfalls."

Ångeby tried the following interesting experiment with pothole no 64. "The depth of this pothole is 7.9 m and the diameter at the opening is 0.8 m. Below this it widens and at a depth of about 5 m, the diameter is 2 m. Near the bottom it contracts to about 0.5 m. A section are to be seen at Fig. 2. In order to obtain a model of the pothole horizontal sections were photographed at intervals of 0.5 dm. In order to get these sections the pothole was slowly filled with water and sawdust was strewn on the surface. A kind of triangulation was arranged with strings and wooden bricks according to six sections. At the Geographical Institute the sections were reconstituted on a horizontal plane. This model in scale of 1 : 4 is now to be seen at the Nämforsen power-station. This pothole is spirally

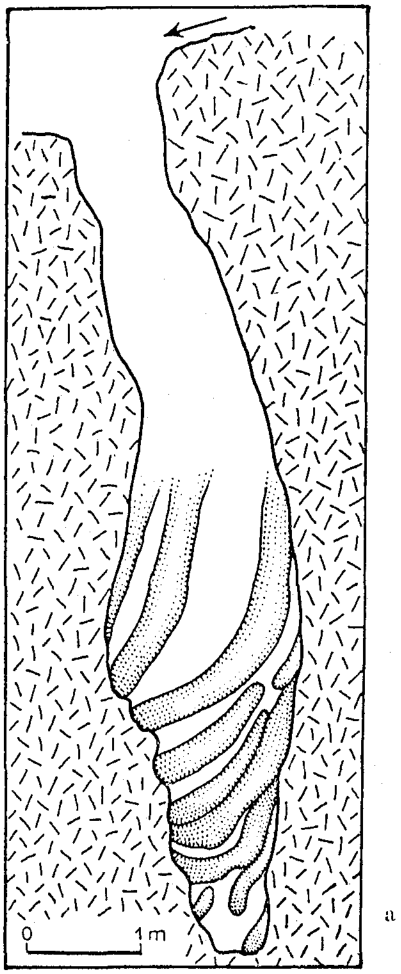

Fig. 2 A pothole between Brådön and Notön near Nämforsen, North Sweden (Pothole no. 64 after ÄNGEBY, 1951, p. 21).

grooved with 5 furrows (see Fig. 2). At a height of 1.7 m from the bottom there is a ledge, and pothole is divided into two sections. It was filled with grinding tools to a height of about 2 m. When the pothole was emptied it was observed that the grinding tools were highest at the center. During the experiment about 210 m^3/sec water let through the hatches. The streams in the pothole moved anti-clockwise and downwards along the furrows. Thus it went downwards along the walls of the pothole and upwards in the center.

It has been supposed that this pothole might possibly be of glacial origin. As against this theory the following facts may be stated : 1) the pothole under discussion is situated in the recent waterfall, 2) the pothole did not contain any moraine, which is usually the case with glacial potholes, 3) the pothole was emptied for the first time in 1949 and the grinding tools were put down again. When it was emptied for the second time in 1950 all the grinding tools had been in movement. 4) the lower part of the pothole is freshly eroded, which is not the case with glacial potholes."

We consider that ÄNGEBY emphasized the eddy theory about origin of general potholes, but at the same time, he recognized "glacial pothole".

C. Glacifluvial Theory

LJUNGNER (1930) of University of Uppsala studied in detail the plastically sculptured erosion forms in Skagerrak coast, Sweden. DAHL (1965) classified them into Sichelwannen, cavettos (Hohlkehle *in* German), channels, bowls, and potholes. DAHL (*op.cit.*) said "LJUNGNER interpreted that these depression forms were eroded by glacifluvial flow, *i.e.* sub-glacial melt water. He mentioned that most Sichelwannen occurred in some kind of depression, for example, in connection with roches moutonnées or sheet fronts, and obstacles in the underlying bedrock had initiated the forms, and they were traces of turbulent flow which arose in the boundary layer between water and rock. LJUNGNER considered that potholes and Sichelwannen etc. might later have been modified to a certain extent by the ice. He mentioned that there was sub-soil-water would have run below the ice, if the sub-soil-water level reached to about ninetenths of the thickness of the ice. He interpreted that potholes were formed by frictional erosion with water rushing between the ice and the substratum, and that sand-dunes, ripples, snow-drifts, and melted forms on surface of drifting ice, were similar to the various depression forms associated with potholes."

JOHNSSON (1956) of Lunds, Sweden, mentioned that potholes and Sichelwannen were eroded by plastic ice and "ice-water paste", and that cavettos were in situations in which the ice had been deflected topographically and cavettos had striae, and the presence of the "ice-water paste" had been supported by HÖPPLER (1941).

In her discussion of the eroded forms at Fischbach am Inn, south Germany, EBERS (1961) considered that the forms were formed mainly by the action of sub-glacial water but were later filled with ice, which polished them with the mass of moraine. She also pointed out that the forms at Fischbach were directly overlain by gravel and sand, and this fluviatile material was thought to have had been deposited as a delta in the Rosenheimi ice lake. STEFANIAK (1961) pointed out that certain of the forms at Fischbach am Inn seem to require the assumption that the water flowed in definite and relatively narrow channels.

HAYAMI observed in summer of 1983 some potholes on granite in a river situated at height of 1,500 m high in Schwarzwald, Germany, which was smaller than the Kurokawa River. (Fig. 3). Their morphology, dimention, and occurrence were a little similar to those of Yakama potholes in the Kurokawa River which were regarded as erosion of water. The following explanation was indicated of a bulletin board in Schwarzwald :

Fig. 3 A pothole in granite in Schwarzwald (photographed by HAYAMI in 1983).

In der Eis-und Nacheiszeit durch Schmelzwasser ausgemahlener Strudeltopf in hartem Granit. Mit einem oberen Umfang von 12 m ist diese Gletschermühle die größte ihrer Art im Schwarzwald. Im Jahr 1955 wurde sie von Prof. Dr. Erwin Litzelmann, Höllstein, freigelegt. Daneben der *Krai-Woog-Gumpen*. Wasserfall des Schwarzenbaches, der hier über einen harten Querriegel aus Granit-Porphyr in ein breites Strudelbecken (=Gumpen) stürzt.

We will compare the potholes in Schwarzwald with those in other countries. As seen in Fig. 3, a very smooth curved outline of the potholes in Schwarzwald is not exactly similar to that of potholes in the Kurokawa River in Japan (see many photographs in Part I), but rather similar to that in "plastic moulded forms" in Norway (GJESSING, 1967, Fig. 10 at p. 19) (Fig. 4). GJESSING stated, "Rounded and smooth forms of the bedrock surface as well as cavities and sinuous courses produced by ice scouring often give the impression of having been moulded by a plastic substance. Therefore, the terms 'plastic scouring', or 'plastic sculpture' are introduced. As it has often been difficult to imagine that several of these plastic scouring forms are made by the glacier ice itself, the idea of a 'subglacial erosion' by a separate subglacial eroding substance has been introduced (*cf.* LJUNGNER, 1930 ; JOHNSSON, 1956) (at p. 1). . . . All over the Portør area roche moutonnée-forms and plastic moulded rock surfaces are found. Most frequently the horizontal projections of the striae are straight lines. At some of the roche moutonnée-formed elevations, however, the striae reveal a 'plastic' deflection. Where the direction of main ice movement was along the axis of the roche moutonnée the deflection seems to have been symmetric (Fig. 10. i.e. Fig. 4 of this paper), resulting in striae smoothly curved round the stoss sides ; curved in the horizontal as well as in the vertical projection (at p. 12-13)."

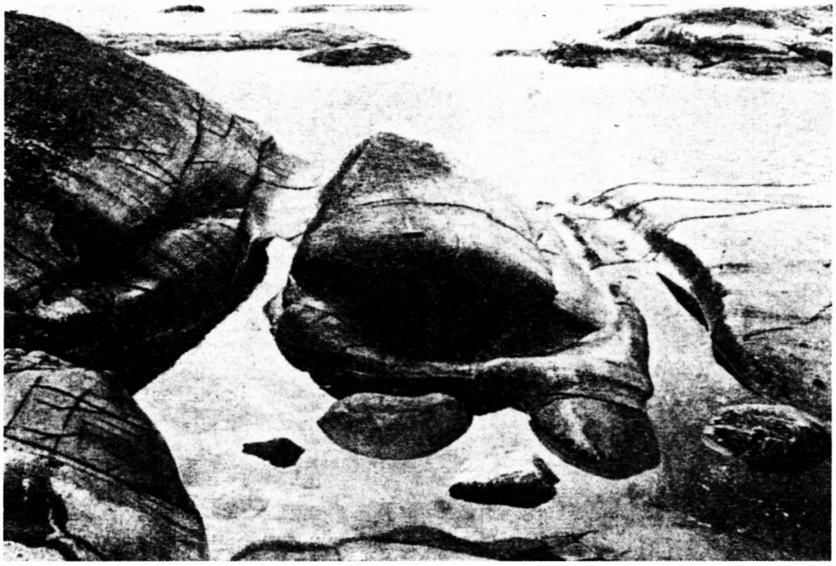

Fig. 4 Plastic moulded forms with symmetric deflection of striae at the stoss end of a roche moutonnée, in the Norwegian Skagerrak coast, after GJESSING (1967, p. 19).

We will compare the pothole in Schwarzwald (Fig. 3) observed by HAYAMI with that in Southwest China observed and assumed as 'subglacial erosion' by SATO in later section (cf. Fig. 9).

D. Eddy Theory

In Japan, the eddy theory and its hydraulic experiment of ALEXANDER (1932) were introduced in detail by ITOH (1979), and so we will mention briefly about them. The obvious difficulties connected with the glacialmill hypothesis and the lack of accurate data on the mechanics of pothole action led ALEXANDER (*op.cit.*) to undertake a series of experiments. He made an apparatus of a glass cylinder of which diameter was 8 inches and depth was 36 inches, and an entrance conduit (A in Fig. 5) was set on the top of the glass cylinder and angle of nozzle of conduit could be changeable. A small amount of sand and some marbles were placed within the glass cylinder. A red ball about three-quarters of an inch in diameter which density was just slightly greater than that of the water was also placed in the cylinder. This ball, being easily carried by the moving water, acted as a visible indicator of the currents set up in the column of water. When a jet of water was placed on inner wall of cylinder, a whirling current was generated. If the angle of jet was varied from 30° to 70° measured from the horizontal, revolutions (or rotation) of the whirling reached maximum value (34 to 36 revolutions /min.). If angles of them were 5°, 10°, 80°, and 85°. revolutions/min. were 16, 23.5, 25, and 4, respectively. Therefore, relative energy of rotation was maximum at angle of 30° to 70°, and it decreased to 50 to 60% at angle 20° to 80°. When depth of the cylinder was equal to its diameter, the energy of rotation was maximum at constant of angle of jet. The energy of rotation decreased to 61, 41, and 22%, if depth of the cylinder increased to 2 times, 3 times, and 4 times, respectively.

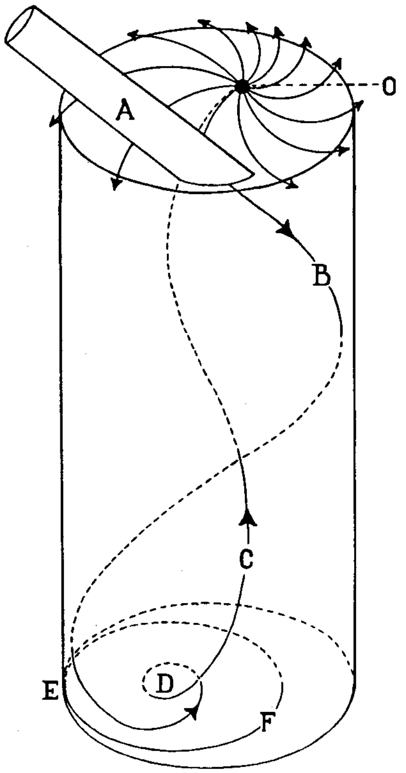

Fig. 5 Motion of eddy current in a glass cylinder, an experiment by ALEXANDER (1932, p. 318).

ALEXANDER (*op.cit.*) explained motions of eddy current within the glass cylinder as shown in Fig. 5. Motions of water current conducted from an entrance conduit A could be traced by a red ball mentioned above. An eddy current along inner wall of cylinder descended to bottom in spiral motion (A→B→D), and an axis of eddy was formed along a central longitudinal line. A center of eddy current on bottom was eccentric compared with a center of cylinder. A red ball and sand grains within cylinder were moved in circular motion by centrifugal force, and they collided with inner wall of cylinder. The sand grains descended down and gathered near an eccentric center and were deposited in cone shape according to their sizes after the circular motion. Very light and very fine-grained sands ascended with spiral ascending current generated around the cone deposit, and they escaped out from cylinder (D→C→O). When crystals of potassium permanganate were dropped in just after the jet was cut off, they were moved into the center with the sand and colored streams from them could be seen rising from the top of the cone, the diffusion of the rising color forming a distinguishable colored axis in the cylinder and showing that an upward current existed at the center. If depth of cylinder become a little larger than its diameter, the sand grains could not escape and deposited on bottom.

Cause of spiral fluting was interpreted as follows. The false bottom previously used to vary the depths of the glass cylinder was placed at the bottom of the cylinder with a small amount of sand on it and the jet opened. When the column had reached its maximum rate of rotation, as shown by the activity of the sand as it whirled about an eccentric point at the bottom, the false bottom was slowly raised by means of the attached rod. As the length of the cylinder was thus gradually lessened, the whirling pile of sand slowly changed its position, moving once around the center for a decrease in depth of the cylinder of about three diameters. As the depth was again increased, the whirling sand heap traveled in the opposite direction about the center. It was often noted when the water was first turned on in these experiments that a spiral line of fine bubbles appeared, evidently marking the real axis of rotation of the water column where dissolved air was freed by the decrease in pressure due to centrifugal force. These results appear to demonstrate the spiral form of the vortex axis in the water column. The working end of this axis is obliquely directed and off center at the bottom of the cylinder, and this off-center position moves about the axis of the hole as it is deepened. The spiral vortex thus acts a sort of spiral tool and under favorable and constant conditions drills into the rock in "corkscrew" fashion, thus giving rise to spiral fluting.

E. Cavitation Theory

In Japan, cavitation theory is not well known among geologists and geographers. HJULSTRÖM (1935) of University of Uppsala, Sweden applied at first time cavitation theory to origin of pothole. However, until then the eddy theory of ALEXANDER (1932) etc. had been circulated in the world.

Therefore, most geologists and geographers did not notice to the cavitation theory until BARNES (1956) and DAHL (1965) appriciated this theory and insisted that the cavitation theory which had been developed in hydraulic engineering should be applied to interpretation of geological and topographical phenomena.

A cavitation phenomenon was discovered when an expected speed could not be attained in a trial voyage of British destroyer, DARING in 1894. It is said that a name of cavitaion was used in a paper of EULER (1754) who described a theory of turbine. When a British battle ship, DREADNAUGHT rotated propeller in around velocity of 85 m/sec, extensive erosion occurred on surface of propeller and many scholars began to study (FLÜGEL, 1926 ; ITAYA, 1966).

A papaer of HJULSTRÖM (1935) is a detailed book in 307 pages as to morphological activity of rivers based upon hydrodynamics, and contains a first proposal of "HJULSTRÖM's Diagram" wellknown in sedimentology. He mentioned as follows.

In natural water courses are always found gases, dissolved in larger or smaller quantities, above all gases of the air, especially oxygen, nitrogen, argon and carbonic acid. Their volume relation in solution is not the same as in atmospheric air. It should be especially observed that the volume relation between O_2 and N_2 in water-absorbed air is 1:2, while in atmospheric air it is about 1:4 (KRÜMMEL, 1907). Oxygen's absorption-coefficient is twice as large as nitrogen's. According to HENRY's law, the amount of gas absorbed by the water is proportional to the pressure of the gas. If the pressure in the liquid is below the pressure which corresponds to the saturation at the temperature and the gas-content in question, the gas surplus is liberated in the form of bubbles. This gas volume is indeed rather small ; — water contains about 3 volume percent of the air's gases—but can be imagined as playing quite an important role.

This separation of gas which can be observed in swift streams (air bubbles behind stones) causes no erosion. The actual cavitation appears only when the absolute pressure p on a water particle sinks nearly to or below the water vapour tension p_d at the temperature present, that is to say : $p \leq p_d$. The vapour tension p_d depends on the composition of the liquid and on the temperature. The vapour tension p_d is increased to two times at 10℃, four times at 20℃, and about seven times at 30℃, compared with p_d at 0℃. As soon as the pressure sinks below these values hollows and cavities are formed in the water. When eddies are formed the lowest pressure prevails at the center of the eddy, and their cavitation appears often in connection with the forming of whirl-pools. The water is no longer a continuous medium—possibly with solitary air bubbles—but is composed of a gas and water surface. It appears as if the water is boiling in an open vessel at a medium temperature (Osborne REYNOLDS, 1894).

It means of BERNOULLI's formula. If one disregards the effect of gravity and assumes that the working pressure powers are formed only by the air pressure B, one will find that cavitation in a gas-free liquid appears, when the velocity reaches the value of

$$c = \sqrt{\frac{2(B - p_d)}{\rho}}$$

From this, it can be calculated that for a pressure of 760 mm and a temperature of 0° C the velocity becomes 14.3 m/sec——that is to say, a very high value. However, this velocity decreases with the air pressure, that is with the height over the sea. When the height increases, this velocity decreases, and it becomes 9.8 m/sec at 6,000 m of the height over the sea. The average velocity in large rivers attains seldom more then 3 m/sec, while in the wild mountain streams it rises to 5 or 6 m/sec (PENCK, 1894). In water-falls with freely falling water-jet, the velocities of stream are 15, 20, and 24 m/sec at heights of 11.5, 20.4, and 30 m of water-falls, respectively. Therefore, the velocities required for cavitation appear in water-falls quite often.

When the velocity decreases, the pressure is increased and the hollows collapse. This collapse takes place with the production of very sharp noises and violent impacts. In an experiment with contraction in a tube, cavitation at the narrowest portion of the tube where the velocity is the greatest is apparent by the formation of a white non-transparent foam. When then, due to an increase of the cross section the velocity is decreased, the pressure increases and cavitation ceases at a sharply marked line. This sudden pressure-increase in a liquid at the increase of area of the cross-section corresponds, in a natural stream, to the hydraulic jump shooting state of motion. Water stream becomes shooting in a rapid stream in a river in mountain with slope steeper than 0.0039 (BOUSSINESQ, 1877). Rapid instantaneous photographs show that the bubbles are pressed together along the longitudinal line so that the back wall bounces against the front wall. FÖTTIGER (1926) calculates the pressure to 1,400 atm., assuming isothermal compression. SCHRÖTER (1934) observed that rubber, which was exposed to cavitation, already after three min. was so heated that it partially melted away and was deformed. Finally, the bubbles become electically charged by the presence of an electric bubble-layer. The ozone odour which can be noticed near water-falls, indicates the presence of strong electric fields.

These pressure-blows similar to hammer strokes cause a corrosive influence which is extremely feared within technics. Metal surfaces are eaten away with unparallelled speed. Above all, propellers, turbines and pumps are exposed to this type of corrosion. The time in which these atacked parts are practically unfit varies in certain cases 1-2 hours' and a month's activity (FÖTTIGER, 1926). Parts of metal surface corroded by cavitation show a typical appearance (Fig. 6, after BARNES, 1956). Thus is formed a highly gorged, porous surface which has the appearance of having been fretted ; it is in

Fig. 6 Cavitation erosion of a steel plate ; 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), after BARNES (1956, p. 498).

rather sharp contrast to the polished appearance which is caused by the wearing away by sand. At high pressures and high temperature a strong active chemical influence must be considered, especially that of O_2. Furthermore, a disintegration of carbonic acid gas (H_2CO_3) into carbonid oxide (H_2CO) and O_2 may be assumed ; O_2 may combine with N_2 and form nitrogen-forming oxides, etc. At high velocity of the flowing water, the chemical activity is highly increased. The weakening of the matter caused by the pressure blows becomes apparent by the formation of microscopically small cracks in which the gases find an extended action-field. If the flowing liquid contains solid particles in suspension their corrosive influence will be increased enormously. A particle which is close to the collapsing liquid-wall receives an acceleration which is of very short duration. According to COOK (1928), a wall of a collapsing hollow should have a velocity of 730 m/sec. It has be shown that a rough crystalline alloy is attacked violently in a short time even if it is extremely hard, while a structure, as far as possible fine-grained, with a velvety appearance resists all attacks incomparably better (Hydraulische Probleme, FLÜGEL, 1926). There is no doubt that solid rocks are corroded as an example exists of the corrosion of quartz in petrology. Quartz used in a membrane for under-water signalling was rapidly destroyed (FÖTTIGER, 1923). As the occurring erosion form, we might expect a groove, straight or curved. If the limiting surface has the form of a rotation-surface, the surface of contact may assume the shape of all kinds of conic sections, as ellipses, hyperbolas, parabolas, or straight lines. The very common forms of cavitation erosion show the shallow hollows and the heart-shaped figure on the metal surface (DE HALLER, 1933 : ACKERET, 1932 : SCHRÖTER, 1934). SCHRÖTER (1933) shows how a hole in a metal surface causes cavitation erosion in the shape of a ribbon in the direction of the stream. The most favourable conditions for the occurrence of cavitation are found in water-falls and under a glacier. When the great ice caps during the Quaternary glaciation reached the period in their recessive state, a very high hydrostatic pressure must have been prevalent there. The most important form among the glacial and fluvioglacial forms of erosion in solid rocks is "Sichelwannen" (the sickle trough) (LJUNGNER, 1930). It consists of a hollow in the solid rock of a groove or bow shaped appearance. It is highly similar to those forms obtained through erosion by cavitation. One may easily be interpreted as marks from cavitation erosion among some erosion pictures granite island in the Nile River at the first cataract and from the north slope of the Swiss Alps which were described by BRUHNES (1902). These may possibly serve as the first beninning of potholes. In natural streams a cooperation always exists between the three types of erosion : 1) erosion by cavitation, 2) eversion and 3) wearing by transported mineral matter. Type 1) does not require the presence of mineral matter or rock fragment. On the other hand, types 2) and 3) require the presence of those matter. The relative effectivity of three types varies greatly with different types of rock. But it must be regarded as being probable that erosion by cavitation plays a rather important part in the forming of canyons.

Next, a cavitation theory of BARNES (1956) of Columbia University, is mentioned. In most phases of hydraulic engineering cavitation presents a serious problem ; therefore, much pertinent matterial 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. Cavitation eroded to a maximum depth of 18 inches of concrete in a dam spillway in 23 hours, and this phenomenon was evidently interpreted by cavitation (BALL, 1947). Cavitation may be an important agent in the erosion of rock by glacial meltwaters and by high velocity streams. If the velocity is sufficiently great, the pressure drops to the vapor pressure of water and "stream" 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. 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. Experimental results gave 30,000 atmospheres as a minimum pressure (VENNARD et LOMAX, 1950). A minor electrical and chemical effect is also known, and there may be other unknown effects. The temperature at the collapse of a bubble has been calculated at 2,700 K (RUTENBECK, 1941), and cavitation erosion with the appearance of fusion in test samples has been cited (NOWOTNY, 1942). BARNES (*op. cit.*) has observed carboncoated gobular forms due to fusion on an iron surface and the odor of burning rubber. High speed motion pictures show a cyclic collapse and regrowth of bubbles (KNAPP, 1952).

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. 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 velocity (ROUSE, 1950). 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% 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. The following conditions are assumed :

velocity distribution :
  constant velocity over the normal section
streamline configuration :
  local velocity at cavitation point
  (v_2) = 2 × mean stream velocity (v_1)
water temperature : 70° F (vapor pressure = 0.36 1bs/sq.in)
surface pressure : 14.7 1bs/sq.in (sea level atmospheric pressure)

air content of water : insignificant
stream flow : as a homogeneous fluid (undispersed)

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

where ;

v_1 = mean stream velocity
p_1 = absolute pressure = 14.7 lbs/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/sq.in
z_2 = elevation of stream bottom = 0 (assumed datum)
γ = specific weight of water = 62.4 lbs/cubic ft
g = acceleration of gravity = 32.2 ft/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. The derived equation gives the following conditions for the initiation of cavitation :

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

For water to attain a velocity of 27.6 ft/sec, a free fall of only 12 ft 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). An empirical equation derived by EHRENBERGER (1926) and 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 (approx. 9° to 45°).

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

average width : 12 ft
average depth : 3 ft

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

sine of slope angle (s) : 0.153 (approx. 9°)
mean stream velocity : v

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

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

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

The above calculations have shown that cavitation may occur at 27.6 ft/sec at a depth of 3 ft and also that a slope of 9° is sufficient for a velocity of 65.5 ft/sec in a stream 3 ft deep by 12 ft 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.

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 12 ft in diameter and 60 ft deep, as at Taylor's Falls, Minnesota. 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. To preserve the cavitaton 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.

Dahl (1965) of University of Uppsala agreed also with the cavitation theory, and mentioned as follows. He considered cavitation erosion to be the most plausible explanation of why the quartz veins in a number of the plastically sculptured detail forms on rock surfaces in northern Nordland were just as much or almost as much eroded as the rest of the form surfaces, while on nearby, glacially eroded surfaces the same veins stood out as selective erosional remnants. The movement of the ice was probably jerky and not an even flow. The interval between each jerky movement may have been sufficient for "Sichelwannen" (Fig. 7) to come into existence of a moraine boulder which was tem-

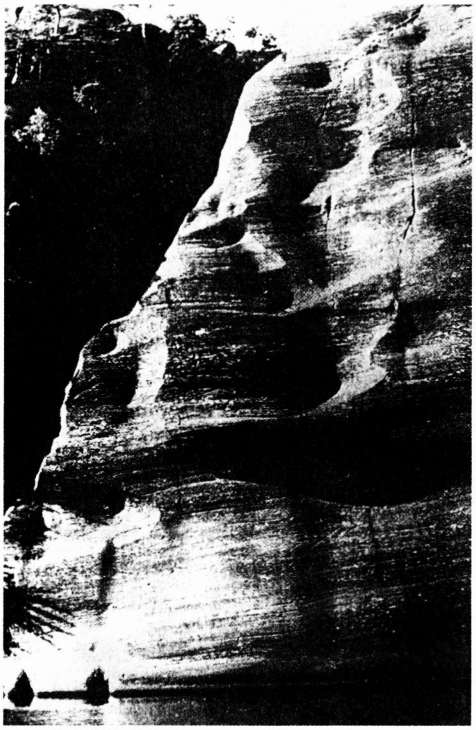

Fig. 7 Sichelwannen (sickle troughs) on almost vertical ice-smoothed rock wall ; Skorpo Island, Hardangerfjord, Norway. Ice flow from right to left. After Holtedahl, 1967, p. 201. (Explanation after Allen, 1982, p. 266).

porarily stationary. The application of GLEN's theory (1954) of the drainage of bodies of water through a restricted tunnel in the ice running in the direction of ice movement would seem to yield the necessary water velocity for cavitation. The great similarity between various plastically sculptured forms and the different erosional forms which has also emerged in modern cavitation experiments (SHALNEV, 1957 : LICHTMAN et WEINGRAM, 1964) is striking and strengthens one's belief in cavitation as an important factor in the creation of the plastically sculptured forms. Cavitation attacks especially the overflow surfaces of dams, monitor–well piers and canal walls beyond spill–way–gate grooves. According to SHALNEV (*op.cit.*) cavitaion erosion of the overflow surfaces of dams is due to unevenness of the surface or to the shape of the dam section. In tunnels, erosion is observed at the entrance to the tunnel when the entrance is obtuse and poorly streamlined and beyond bends in the lengthwise axis of the tunnel.

Most of the plastically sculptured forms display highly polished and sometimes blasted surfaces. As cavitation erosion creates coarse surfaces, we should also reckon on a glacifluvial corrosion effect. One important question is whether corrosion alone can conceivably create plastically sculptured forms under special conditions of pressure and water flow or whether cavitation is required first. DAHL (*op.cit.*) observed forms resembling plastically sculptured forms in a wadi in Israel. As regards shape and size, there seems almost to be a difference in degree between the real plastically sculptured forms and the elements resembling p.s. forms observed by DAHL in recent water–coursed. The latter are usually less sharply sculptured and more irregular than real p.s. forms and do not have a strict orientation. The fact that atypical p.s. forms may also occur outside glaciation areas and in environments in which the conditions for cavitation must have been restricted gives an indication that the typical plastically sculptured forms may be results of the combined action of cavitation and corrasion.

Ⅲ Significance of Pothole Research

Is the pothole only a sort of hollow formed on surface of rock, and is it only a sort of special morphology eroded by river or glacier? What is academic value of pothole as natural monument? Does the pothole eroded in river belong to a sort of "Uniformitarianistic erosion" which was formed very slowly for all geological ages and at the same time, was destroyed very slowly for later geological ages? Does the pothole distributed in the formerly glacier region and formed by a sort of glacier erosion, belong to "Catastrophic erosion"? Did a great flood age exist after the Würm glacial stage? How many years does the erosion of a giant pothole require? Is there any morphological difference between potholes in the formerly glacier region and those in tropical or subtropical region? We consider that answers to some problems mentioned above seem to be very imperfect if we read extensively many literatures about potholes in the world.

A. Uniformitarianistic Erosion or Catastrophic Erosion

TSCHANG Hsi-lin (1958) said, "In upper stream of the Chilungho River, north Taiwan, some potholes were seen even on big boulders in the stream. These potholes seem to be formed after the boulders have transported there. Then the formation of potholes is only of a very recent phenomenon. Amount of rainfall reaches 6,572 mm in a year in the Chilungho River. There is nearly no distinct dry season all around the year, the supply of running water is so abundant that the erosion power is particularly strong, thus it favours the development of potholes. North Taiwan has been uplifted during the recent age, and the dry up of Taipei Lake (now the Taipei Basin) is also a very recent phenomenon. This is evidenced by the presence of many terraces, incised meanders and valley-in-valleys along streams. As the stream valley rejuvenated, the base level of erosion is lowered, vertical corrasion becomes stronger, and then potholes are easily formed. The potholes are varying in diameter from 3 cm to 440 cm, and the diameter of most potholes is between 10 cm and 50 cm. Potholes varying in depth from 2 cm to 285 cm, and the depth of majority is between 10 cm and 50 cm. Potholes of North Taiwan occur between 0 and 8 m above the low stream water surface. Most of them are found within 50 cm above the water surface."

We consider that potholes in much rainfall region as Taiwan might be formed by the "Uniformitarianistic Erosion" in very recent time. However, in the Kurokawa River, Japan, fallen big boulders of some thousands tons do not seem to have fallen in very recent time, based upon our observation of some big boulders (5 m × 10 m) with potholes. A water level of the Kurokawa River rose up to a level 5 m higher than normal level in a heavy rain of typhoon at August 26, 1982, when some potholes on big boulders were covered by rapid whirling stream and might be eroded a little for nearly 24 hours by cavitation or eddy erosion. If a heavy rainfall which make the water level of the Kurokawa River rise up to 5 m would happen one time per 10 to 30 years, these potholes on fallen big boulders might be formed by the "Catastrophic Erosion".

We must observe how many centimeters these potholes on fallen big boulders in the Kurokawa River, for example potholes under Ohzaru (*lit.* Big Monkey) Fall, will be erode in next future heavy rain in interval of 10 to 30 years. Therefore, we consider that these potholes in the Kurokawa River have a very important academic value to determine the "Uniformitarianistic" or "Catastrophic" erosion of pothole.

We compare potholes in the Kurokawa River of Japan with those of North Taiwan mentioned above. Amount of precipitation (both of rain and snow) in the Kurokawa River region is about 3,000 mm in a year, and it is less than a half of the Chilungho River region of North Taiwan. Amount of uplift of the Shikoku Mountains including the Kurokawa River region, seems to be less than North Taiwan. Because height of the Shikoku Mountains is 1,000 to 1,900 m above sea level, and that of the Taiwan Mountains is 2,000 to 4,000 m. We estimate that amount of uplift of Shikoku correponds to a half of that of Taiwan. The smaller precipitation and smaller uplift of the Shikoku Mountains show perhaps the smaller erosion energy of potholes, compared with Taiwan. However, diameter of potholes in the Kurokawa River is 50 cm to 800 cm and most of it is 100 to 200 cm. Depth of potholes of this River is 50 to 1,000 cm and most of it is 100 to 200 cm. The potholes in this river occur between 0 and 25 m above the low water surface, and most of them are found in 1 to 10 m above the low water surface. Therefore, the larger dimensions of potholes and the higher occurrence above water surface in this River suggest the older formation age of potholes and the longer duration of pothole erosion, compared with those of North Taiwan.

B. Flood Age after Würm Glacial Stage

HOLTEDAHL (1967) of Bergen, Norway, said, "As regards the Hardangerfjord, the delgaciation probably took place fairly rapidly. There was a retreat of the ice front during Late-glacial times, with a readvance of the main fjord-glacier resulting in very distinct terminal moraines and in very marked lateral moraines. This readvance is thought by the author to represent the Ra-substage, and opinion which is also held by UNDAS (1963). Recent radio-carbon datings of shell fragments in till have strongly supported this suggestion. From the first locality, 44 m above sea level, *Mya truncata* fragments in clayey till gave the result 11,470 ± 180y.B.P. and from the second locality fragments of *Zirphaea cristata* in clayey till below sandy gravel, 38 m above sea level, gave the result 9,940 ± 160y.B.P. At Bu, about 12 km from the head of the fjord, at an altitude of 110 m, and organic sediment was pollen-analytically examined and showed a possible pre-Boreal age (ANUNDSEN, 1964). This was confirmed by C^{14} dating of the same material, which gave an age of 9,720 ± 330y.B.P. It is therefore clear that the fjord-glacier has had no readvance or standstill for any length of time between the Halsnoy stage and the Eidfjord stage (which is marked by the huge glacifluvial ice contact acumulation at the head of the fjord.)" Pre-Boreal age indicates a cold age after late ice age and its time range is 11,000 to 10,000 years ago.

ÄNGEBY (1951) said, "At Nämforsen (in Sweden) there are a number of rocks that are only covered by the stream at high water level. These rocks were used by the men of the stone age for petroglyphs, mainly consisting of elks, boats, men etc. They have been curved only a few milimeters deep into the rock, but they are still very well preserved. These petroglyphs are supposed to be about 4,000 years old and are proof that erosion and weathering during the period since has not had a very great effect." Therefore, ÄNGEBY (*op.cit.*) considered that potholes at Nämforsen were older than 4,000 years old.

We consider that most potholes in the formerly glacier region in Scandinavia might perhaps have been formed for a relatively shorter time of much rain which corresponded to a warm and wet Atlantic stage (about 7,000 to 4,500 years ago) after a cold and dry Boreal stage. The rapid retreat of fjord glacier in Norway mentioned above suggests that a transition from the Boreal stage to Atlantic stage might have been rapid. The Atlantic stage corresponds to the Flandrian and Lithnis transgressions (7,000 to 4,000 years ago) and to the Jomon or Yurakucho transgression (about 5,000 years ago) in Japan, and it is said that temperature was 2 to 3° C higher than the present. When we suppose based upon a paleoclimate graph of snow line altitude curve in Norway, this transition time from colder to warmer stages has duration of about 1,500 to 2,500 years. We suppose that this transition time might have perhaps corresponded to a "Flood Age" written in older legend books of some tribes in the world, and it might have been 8,500 to 7,000 years ago.

We consider that this "Flood Age" might have corresponded to a description of LJUNGNER (1930) that "potholes were traces of turbulent flow which arose in the boundary layer between water and rock". Potholes and Sichelwannen might have perhaps been formed during a relatively shorter time in the "Flood Age". We can not deny a possibility that potholes in Japan which had mountain glacier in Würm glacial stage in its northern and central parts of Japan, might have been formed in a transition stage after the Boreal stage (*i.e.* "Flood Age"). We consider that potholes in tropical or subtropical regions, such as Taiwan, HongKong, Burma (the Irrawaddy), and Hawaii, were formed by erosion of pure water in all geological ages (*cf.* TSCHANG, 1958, 1964 ; STAMP, 1940 ; KINGSBURY, 1952). ELSTON (1918) said, "Most of the erosion of the holes is apparently accomplised during flood stages."

When did big boulders (nearly 10 m diameter) of chert of late Paleozoic or early Mesozoic fall from steep cliffs in rivers of the Kurokawa and Omogo? Of course, some fallen big boulders have fallen by dint of landslide in a heavy rain of recent typhoon, for example a fallen big boulder of chert from high cliff to a highway and let the highway blockade for 40 days in summer of 1979 at Ochide along the Omogo River. We estimate that a big boulder of chert falls every ten years in present climate and therefore, a thousand big boulders have fallen during 10,000 years. However, total of big boulders in rivers of the Kurokawa and the Omogo seems to reach some tens or hundreds of thousand. Therefore we suppose that a great deal of big boulders might fall during a relatively shorter period, namely "Flood Age" of Japan.

At the beginning of the Jomom transgression, mountain regions of Japan might probably have two or three times of precipitation compared to present time, namely 4,000 to 6,000 mm/y. Recently, a remarkable heavy rain location of 7,000 mm/y was found near Mt. Ohdaigahara in Kii peninsula, Japan. Therefore, we consider that a weather of North Taiwan of 6,500 mm/y of precipitaion may correspond to that of Japan in Jomon age, and that erosion velocity of potholes in North Taiwan is two or three times greater than that in the Kurokawa River of Japan. In Jomom age, turbulent floods seem to have taken place every year in the Kurokawa River region. We consider that big potholes in this River might have been formed by this "Catastrophic erosion".

C. Possibility of Low-altitude Glacier Hypothesis in Japan

We stated in the preceding report (1983 in Japanese) as follows, "Some lateral holes beside vertical cliffs at Matsuura deep and Ohzaru Fall resemble somewhat to Sichelwannen in Norway, although they have no horizontal striae by glacier unlike Sichelwannen. Can whirling water stream mentioned by ALEXANDER (1932) erode these lateral holes? We speculate that our research of potholes at Yakama (*lit.* Eight Cauldrons) in the Kurokawa River may develop to an interesting theme of 'a posibility of glacier in Shikoku Island.'"

When SATO surveyed geology of Mt. Ishizuchi (1982 m high) (see Fig. 1-a of Part Ⅰ) a few years ago, he observed a nearly U-shaped valley between Mt. Tengu and Mt. Nansenpo (*lit.* South Peak), and this valley resembled rather the true U-shaped valley in the Hida Mountains, so-called the Japanese North Alps. Therefore, we surveyed supposed glacier topography in topographical maps in scale of 1:25,000 in Shikoku Island. We found some supposed glacier topography, and among them, the most probable U-shaped valley was situated in the source of the Iya River on northwest slope of Mt. Tsurugi (*lit.* Sword Mountain) (1955 m high) (see Fig. 1-a of Part Ⅰ). We surveyed the probable U-shaped valley near Mt. Tsurugi, as well as the famous giant potholes at Dogama (*lit.* Earth Cauldron) along the Sadamitsu River and some broken potholes near Ichiu Electric Power Plant along middle stream of the Iya River (see Fig. 1-a of Part Ⅰ). However, we could not find any evidence such as ice striae and moraine, and the probable U-shaped valley was covered partly by landslide deposits.

SATO and other Japanese geologists surveyed South Sichuan and West Yunnan Provinces of China in 1983 and 1984, with cooperation of Chinese geologists of Institute of Geology, Academia Sinica, Beijing (Peking). SATO observed some potholes and probable U-shaped valley in the Anninghe River region of South Sichuang Province (Fig. 8). Mr. LU Defu, Chinese geologist, explained to SATO how to discriminate the glacier striae on surface of boulder. Some potholes in the Anninghe River (Fig. 9) did not resemble to a roughly eroded pothole by water in Japan, but resembled to a plastically sculptured pothole by glacier in Norway (see a photograph of Fig. 4). Some probable U-shaped valleys in the Anninghe River (Fig. 10) were interpreted as product of periglaciation by some Chinese geographers (Compil. Comm. Nat. Geogr. China, 1980 ; Quatern. Glac. Geol. Commit., 1982 ; SATO, 1986). Locations of probable U-shaped valleys and striae boulders are situated in latitude of 27°00′ to 28°30′ N and in the altitude of 1,000 to 2,000 m.

A reason why SATO speculates possibility of low-altitude glacier in Japan, is as follows : 1) LEE (1933) mentioned that U-shaped valleys, moraines, and striae boulders occurred at slope of 800 to 1,300 m above sea level of Mt. Lushan along middle stream of the Yangtze River, althouth some European geologists, such as BARBOUR (1934), refused this proposal. 2) Recent Quarternary glaciology in China developed based upon the theory of LEE (1937), although some geologists and geographers in China do not agree with the theory of LEE (Quatern. Glac. Geol. Commit., *op.cit.*). 3) East China has been suffered sometimes by cold waves, and the average annual temperature is very lower than the same latitude area of the world, and that of East China in 30° N is almost equal to that of West Europe in 50° N (South England). 4) It is said that the Tibetan Plateau was 2,000 to 2,500 m lower in altitude than the present in Lushan (Riss) glacial stage (GUO, 1976). Therefore, strong west wind influenced East China until the end of middle Pleistocene, and the cold wave was greater than the present, and snow line in East China was lower than that in West China. 5)

Fig. 8 A map of East Asia. T : Tsugaru, KI : Kitakami, H : Hida, N : Nagano, K : Kii (Japan), C : Chilungho River, L : Mt. Lushan, A : Anninghe River, TB : Tibetan Plateau, HK : Hong Kong (China), M : Mongor, AT: the Altai Range, I : Irrawaddy River, Y : Yangtze River.

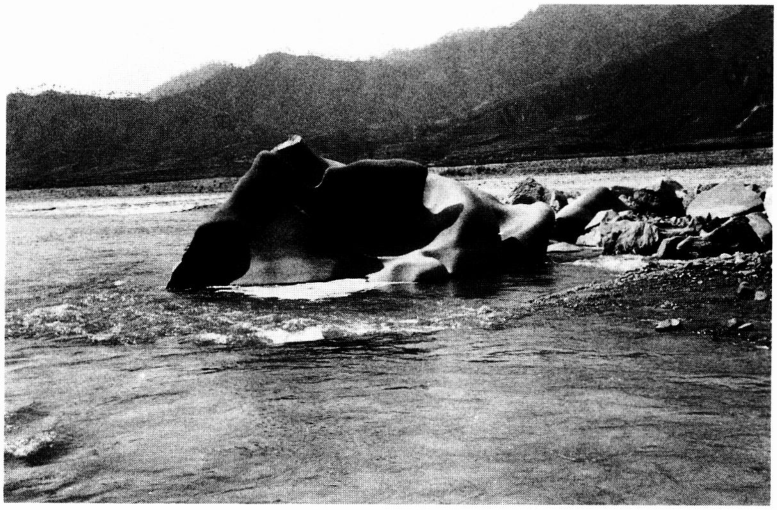

Fig. 9 Potholes with very smooth inner wall in the Anninghe River, South Sichuan Province, China ; this morphology is similar to that in Norway formed by subglacial erosion ; after SATO (1986).

Fig. 10 Probable U-shaped valleys in the Anninghe River region, South Sichuan Province, China ; upper : north of Chaho, lower : Lizhuang ; after SATO (1986).

Mountains in Mongor and south Siberia, for example the Altai, might be lower in altitude than the present before Riss glacial stage.

Based upon the above-mentioned evidences, SATO speculate that great cold waves swept Korean Peninsula and Japanese Island and let the low-altitude glacier develop in middle or late Pleistocene. According to the low-altitude glacier hypothesis in 1930-35, lower limit of glacier was estimated 700 m in Nagano Prefecture, 300 m in Highway of Nakasendo (OGAWA, 1932, 1933), 100-150 m in Tsugaru, and 100 m in Kitakami Mountains.

OKAMOTO (1963, 1972) and MORIYA (1967) proposed a new hypothesis of low-altitude glacier. If this hypothesis is true, periglacial erosion might occur in Shikoku Mountains in 1,000 to some hundreds meters high.

IV Conclusion

1) Moulin (shaft in glacier) hypothesis had continued for nearly a hundred years until appearance of Eddy theory in 1932, but after then FAEGRI (1952) and others supported the Moulin hypothesis.

2) A hydraulic experiment and Eddy theory of ALEXANDER (1932) have been supported by many geologists and geographers. However, we consider that some side holes, such as Sichelwannen, and shallow holes with uneven walls can not be explained only by Eddy theory.

3) HJULSTRÖM (1935) applied at first Cavitation theory, developed in hydraulic engineering, to origin of potholes, and BARNES (1956) and DAHL (1965) supported Cavitation theory. We consider that the shallow holes with uneven walls can be explained by this theory.

4) We consider that some potholes might have been formed by Uniformitarianistic erosion which needed longer duration, but the other potholes might have been formed by Catastrophic erosion, such as Cavitation.

5) The Catastrophic erosion might have occurred in "Flood Age" which happened probably immediately after Würm glacial stage, namely during Flandrian and Jomon transgression stages.

6) SATO (1986) observed some potholes of probable subglacial origin and probable U-shaped valleys in the Anninghe River region, South Sichuan, China in 1983-84. Therefore, he has supported Low-altitude Glacier Hypothesis of some Chinese geologists, such as LEE, J. S. (1933, 1937). He also, speculates a possibility of low-altitude Glacier Hypothesis in Shikoku Mountains based on evidence of potholes.

References

References in Parts I and II are included in Bibliography.

Bibliography of Potholes

Shinji SATO and Tomoko HAYAMI

We collected some literatures about potholes, cavitation in hydraulics, river incision, and low-altitude glacier hypothesis, as well as references in Parts I and II.

ACKERET, J., 1930 : Experimentelle und theoretishe Untersuchungen über Hohlraumbildung (Kavitation) im Wasser. *Tech. Mekanik und Termodynamik*, 1, Jahrg., Berlin.

ACKERET, J., 1932 : Kavitation und Kavitationskorrosion. In *Hydromechanische Probleme des Schiffantriebs*. Veröffentlichung der Vorträge u. Erörterungen d. Konferenz über hydromech. Probleme d. Schiffsantriebs in Hamburg, 227-240.

ADDINGTON, A.R., 1949 : Cauldrons, origin by running water. *Bull. Geol. Soc. Amer.*, v. 60, no. 12, pt. 2, 1935.

AHLMANN, H.W., 1924 : Ragundasjön geomorfologi. *Sverigds Geologiska Undersökning*, Se. Ca. no. 12, Stockholm.

AIGNER, T. and FUTTERER, E., 1978 : Kolk-Töpfe und-Rinnen im Muschelkalk—Anzeigner für Wattenmeer? (Pot and gutter casts in the Muschelkalk—tidal flat indicators?) *N. Jahrbuch f. Geol. u. Paläont. Abhandl.*, Bd. 156, H. 3, 285-304.

ALEXANDER, H. S., 1932 : Pothole Erosion. *Jour. Geol.*, v. 40, 305-377.

ALLEN, J. R. L., 1982 : *Sedimentary Structures. Their Character and Physical Basis*, v. 2, Elsevier Sci. Publ. Co., Amsterdam, 663p.

ÄNGEBY, Olof, 1951 : Pothole Erosion in Recent Water-falls. *Lund Studies in Geography*, Ser. A. Physic. Geogr., no. 2, 1-34.

ÄNGEBY, Olof, 1952 : Recent subglacial and lateroglacial pothole erosion (eversion). *ibid.*, no. 3,

ANUNDSEN, K., 1964 : Kvartaergelogiske og geomorfologiske undersökelser i Simadalen, Eidfjord, Måbödalen, Hjölmodalen og tilstötende fjellområder. *Thesis Univ. Bergen.*

ARNBORG, L., 1957 : Erosion forms and processes on the bottom of the River Angermanalven. *Geogr. Ann.*, no. 1, 32-47.

ASHBURNER, C.A., 1886 : Description of the Archbald potholes, also of the buried valley of New Port Creek near Nanticoke. *Penn. Geol. Surv.*, 2nd Ann. Rept., 615-636.

AUGUSTINUS, P.G.E.F., 1978 : The changing shoreline of Surinam (South America). *Natuurwetenschappelijke Studiekring voor Suriname en de Nederlandse Antillen*, Utrecht, no. 95, 232p.

BAI, Mingyun, 1983 : *Method of geological survey of Quaternary glacier.* 64-65, Geology Press, Peking (*in* Chinese).

BARBOUR, G.B., 1931 : The Taiku deposits and the problem of Pleistocene climates. *Bull. Geol. Soc. China*, no. 10, 71.

BARBOUR, G.B., 1934 : Analysis of Lushan glaciation problem. *ibid.*, no. 13, 647.

BARKER, E.E., 1913 : Glacial potholes at Crown Point, N.Y. *Jour. Geol.*, v. 21, no. 5, 459-464.

BARNES, H.L., 1956 : Cavitation as a geological agent. *Amer. Jour. Sci.*, v. 254, no. 8, 493-505.

BECH, H.H., 1948 : The potholes of Conewago Falls, Pa. *Proc. Penn. Acad. Sci.*, v. 22, 127-230.

BERRY, L. and RUXTON, B.P., 1960 : The evolution of Hong Kong Harbour Basin. *Zeitshr. Geomorph.*, v. 4, no. 2, 97.

BLANK, H.R., 1958 : Pothole grooves in the bed of the James River, Mason County, Texas. *Texas Jour. Sci.*, v. 10, no. 3, 293-301.

BOUSSINESQ, J., 1877 : Essai sur la theorie des eaux courantes. Mem. presentis par divers savants a l'Academie des sci. *Inst. nat. France.* t. 23, no. 1.

BOUVE, T.T., 1889 : Indian potholes or giants' kettles of foreign writers. *Proc. Boston Soc. Nat. Hist.*, no. 24, 218-226.

BREMER, H., 1960 : Neuere flussmorphologische Forschungen in Deutschland und augsgewahlte Probleme der Flussmorphologie deutscher Ströme. *Bundesant. f. Landesknde. u. Raumforschg.*, 283-299.

BRITTON, N.L., 1882 : On some large potholes near Williamsbridge, N.Y. *N.Y. Acad. Sci.* no. 1, 181-183.

BRÖGGER, D.C. and REUSCH, H.H., 1874 : Giant's Kettles at Christiana. *Quar. Jour. Geol. Soc.*, v. 30, 754-771.

BRUNHES, J., 1902 : Le travail des eaux courantes. La tactique des tourbillons. *Mém. Soc. Fribourgeoise des Sc. Nat.* II, 4, *Geol. et geographie*, Fribourg.

BRUNHES, D. and BRUHNES, J., 1904 : Les anagogies des tourbillons atmospheriques et des tourbillons des cours d'eau et la question de la deviation des ribères vers la droite. *An. Geogr.*, v. 13, 1-20.

CHAMBERLIN, R.T., 1905 : The glacial features of the St. Croix Dallers region. *Jour. Geol.*, v. 13, 255-256.

CHARPENTIER, Jean de, 1841 : *Essai sur les Glaciers et sur le terrain erratique du bassin du Rhone.* Lausanne.

COMPILING COMMITTEE of NATURAL GEOGRAPHY in CHINA, ACADEMIA SINICA, 1980 : *Natural Geography in China*, v. Geomorphology, chapt. 8. Glacier Topography, 202-254, Science Press, Peking (*in* Chinese).

COOK, Stanley S., 1928 : Erosion by water-hammer. *Proc. Royal Soc. London*, Ser. A, v. 119, 481-488.

Dahl, Ragner, 1965 : Plastically Sculptured Detail Forms on Rock Surfaces in Northern Nordland, Norway. *Geogr. Ann.* v. 47A, no. 2, 83–140.

Dana, J.D., 1887 : A pothole of remarkable size in Archbald, Pa. *Amer. Jour. Sci.*, v. 3, no. 34, 489.

Davis, S.G., 1949 : *Hong Kong, its geographical setting.* 50p., London.

De Haller, P., 1933 : Unters. über die durch Kavitation hervorgerufenen Korrosionen. *Schweizer. Bauzeit.*, Bd. 101.

Doll, C.G., 1937 : A glacial pothole on the ridge of Green Mts. near Fayton, Vt. *Vermont 20th Rept. State Geol.* on Mine. Indust. and Geol., 1935–1936, 145–151.

Du Toit, A.L., 1951 : The diamondiferous gravels of Lichtenburg. *Mem. Union of South Africa Geol. Sur.*, 44–50.

Eaton, H.N., 1916 : A giant pothole near Scranton, Pa. *Sci.*, N. S. no. 43, 399.

Ebers, E., 1961 : Die Gletscherschliffe und–rinnen. *in* Fehn, H. *ed. Der Gletscherschliffe von Fischbach am Inn.* Landeskund. Forschung., H. 40, 78–84. München.

Edstrand, Hans, 1946 : The effect of the air content of water on the cavitation point and upon the characteristics of ships' propellors. *Swedish State Shipbuilding Experimental Tank Pub.* 6.

Ehrenberger, R., 1926 : Wasserbewebung in steilen Rinnen (Schusstennen) mit besonderer Berrücksichtung der Selbstbelüftung. *Zeitschr. Österreich. Ingeniur–Architekt.*, jahrg. 78, H. 15/16, 155–160.

Ehrenberger, R., 1931 : Direkte Geschiebemessungen an der Donau bei Wien und deren bisherige Ergebnisse. *Die Wasserwirtsschaft,* Jahrg. 1931, Wien.

Eisenberg, Phillip, 1950 : On the mechanism and prevention of cavitation. *David W. Taylar Model Basin Rept.* 712 (Naval Dept.).

Elston, E.D., 1917–1918 : Potholes–their variety origin and significance. *Sci. Month.* V, 554–567 and VI, 37–53, N.Y.

Exner, F., 1919 : Zur Theorie der Flussmäander. *Ak. d. Wiss. Sits–Ber.* Abt. II a, Bd. 128 II, Halbband, Wien.

Exner, F., 1928 : Dünenstudien auf der Kurischen Nehrung. Mit einem Anhang : Über Flussmäander, Wogenwolken und Zyklonen, die durch Reibungswalzen entstehen. *Ibid,* Abt. II a, Bd. 137.

Faegri, K., 1952 : On the Origin of Pot–holes. *Jour. Glaciology,* v. 2, 24–25.

Farrington, O. C., 1899 : Pothole vs. Remolino. *Sci.*, N.S., no. 10, 187.

Finger, Josef, 1878 : Über den Einfluss der Erdrotation auf die parallell zur sphäroidalen Erdoberfläche in beliegiben Bahnen vor sich gehenden Bewegungen insbesondere auf die Strömungen der Flusse und Winde. *Ak. Wiss. Sitz.–Ber.* Abt. II, Bd. 76.

Fischer, Josef, 1913 : Grösste Geschwindigkeiten in fliessenden Gewässern. *Zeitschr. Gewässerk.* Bd. 11, 71–74.

Fleming, M.A., 1899 : The potholes of Foster's Flats (now called Niagara Glen) on the Niagara River. *Proc. Amer. Ass. Adv. Sci.*, no. 48, 226–227

Flügel, G., 1926 : *Hydraulische Probleme.* V.D.I. Verlag.

Fobes, C.B., 1957 : Glacial potholes on Runford Whitecap Mountain. *Maine Field Nat.*, v. 13, no. 1–2, 2–7.

Föttiger, H., 1926 : Untersuchungen über Kavitation und Korrosion bei Turbinen, Turbopumpen und Propellern. *Hydraulische Probleme,* 14–64, Berlin.

Freeman, John R., 1929 : Hydraulic laboratory practice. *Amer. Soc. Mechanical Engineers,* N.Y.

Fujimoto, H., 1966 : Potholes in the Seta River and the Shigaraki River. *Chigaku Kenkyu,* no. 17, 10–12, Kyoto (*in* Japanese).

Fuller, Margaret B., 1925 : The Bearing of Some Remakable Potholes on the Early Pleistocene Glaciation of the Front Range, Colorado. *Jour. Geol.*, v. 33, 224–235.

Gifu and Aichi Prefectures, 1960 : *Research Report of Natural Park in the Kiso River, Hida.* 227p (*in* Japanese).

Gilbert, G.H., 1906 : Moulin work under glaciers. *Bull. Geol. Soc. Amer.*, v. 17, 317–320.

Gjessing, Just, 1965 : On "plastic scouring" and "subglacial erosion". *Norsk Geogr. Tidssk.*, Bd. 20, H. 1–2, 1-37.

GJESSING, Just, 1967 : Potholes in connection with plastic scouring forms. *Geogr. Ann.*, v. 49A, no. 2-4, 178-187.

GLENN, J. W., 1954 : The stability of ice-damed lakes and other waterfilled holes in glaciers. *Jour. Glaciology*, v. 2, no. 15, 316-318.

GOLDTHWAIT, J.W., 1915 : The origin of lost River and its giant potholes. *Sci.*, N.S., no. 42, 834-836.

GUO, Xudong, 1976 : Quaternary interglacial epoch and paleoclimate in Mt. Jolmolungma (Everest) region. *Scientific Survey Report in Mt. Jolmolungma region, Quatern. Geol., 63-78*, Science Press, Peking (*in* Chinese).

HAGA, K., and NISHI, K., 1981 : Explanation of topographical classification map of Mt. Ishizuchi, 1/50,000, *Fundamental Land Classification Survey of Mt. Ishizuchi*, 11-18, Ehime and Kochi Pref. (*in* Japanese).

HATTIN, D.E., 1958 : New evidence of hight-level glacial drainage in the White Mountains, N.H. *Jour. Glaciology*, v. 3, 315-319.

HAYASAKA, I., 1930 : Notes on the Chilung Valley. *Taiwan Tigaku Kizi*, v. 1, no. 5, 60-63, Taipei (*in* Japanese).

HAYASHI, M., 1984 : Geology of Ochide in the Omogo River. *MS of Graduate Thesis, Fac. Educ., Ehime Univ.* (*in* Japanese).

HEDBERG, J., 1942 : Report on steep-slope flow. *Trans. Amer. Geophys. Union*, v. 23, 74-76.

HEIM, A., 1885 : *Gletscherkunde.* Stuttgart. 544p.

HELMERSEN, G.V., 1867 : Das Vorkommen und die Entstehung der Riesenkessel in Finland. *Mem. Acad. Sci. St. Petersbourg*, Ser. 7. St. Petersbourg.

HERSHEY, O.H., 1899 : Pothole vs Remolino. *Sci.*, N.S., no. 10, 58.

HIGGINS, C.G., 1957 : Origin of potholes in Glaciated Regions. *Jour. Glaciology*, v. 3, 11-12.

HJULSTRÖM, Filip, 1935 : Studies of the morphological activity of rivers as illustrated by the River Fyris. *Bull. Geol. Inst. Univ. Uppsala*, v. 25, 221-527.

HOFMANN, A., 1913 : Die Bedeutung der Eversion für die Ausbildung von Erosionsrinnen. *Zeitschr. Gewässerkunde*, Bd. 11, Dresden.

HOGARD, H., 1958 : *Recherches sur des glaciers et les formations erratiques des Alps et de la Suisse.* Epinal.

HOLLINGSWORTH, S.E., 1951 : Potholes and Glacial Mills—Some comments on Dr. R. Streiff-Becker's article ; *Jour. Glaciology*, I, 9, London.

HOLTEDAHL, Hans, 1967 : Notes on the formation of fjords and fjordvalleys. *Geogr. Ann.*, v. 49A, no. 2-4, 188-203.

HORIKOSHI, K., SATO, S., KASHIMA, N., TORIUMI, M., TAKAHASHI, J., and KATTO, J., 1981 : Explanation of surface geological map of Mt. Ishizuchi, 1/50,000, *Fundamental Land Classification Survey of Mt. Ishizuchi*, 19-26, Ehime and Kochi Pref. (*in* Japanese).

HÖPPLER, F., 1941 : Die Plasticität des Eises. *Kolloid Zeitschr.* Bd. 97, 154-160.

IDA, Y., 1977 : Potholes in river in Mizunami City. *Educ. Comm. of Mizunami City, Gifu Pref.*, 1-22 (*in* Japanese).

ITAYA, M., 1966 : *Hydraulics.* 310p, Asakura, Tokyo, (*in* Japanese).

ITIKAWA, W., 1944 : A pothole with spring—Ishikawa Prefecture. *Geogr. Rev. Japan.*, v. 20, no. 2, 134-136 (*in* Japanese).

ITO, R., 1940 : New examples of pothole erosion at the seashore of Inubo, Tiba prefecture and in the valley of Hida-Gawa. *Ibid.*, v. 16, no. 2, 177-193 (*in* Japanese).

ITO, R., 1940 : The distribution and morphology of potholes in Japan, *Ibid.*, v. 16, 773-776 (*in* Japanese).

ITO, R., 1942 : Pothole by marine erosion. *Sci. Ocean*, v. 2, no. 8, 34-41 (*in* Japanese).

ITO, R., 1943 : Classification of river erosion types. *Geogr. Rev. Japan*, v. 19, no. 3, 125-134 (*in* Japanese).

ITOH (*formerly* ITO), R., 1964 : Topographical studies of pothole erosion in Hisuikyo Valley. *Sci. Rept. Seikei Univ.*, v. 2, no. 3, 1-62 (*in* Japanese).

ITOH, R., 1966 : Potholes at Furikusa, Okumikawa Plateau. *Reg. Diagnosis Rept. Toei Town, Aichi Univ.*

Educ., 55–59 (*in* Japanese).

ITOH, R., 1979 : *Pothole erosion in Japan.* Kokin Shoin, 1–132 (*in* Japanese).

ITOH, R., 1982 : Pohtoles in the Oga River on south slope of Mt. Asama. *Geogr.*, 10 (*in* Japanese).

ITOH, R., 1984 : Pothole researches in Japan. *Res. Rept. "Yakama Potholes", Special Natural Monument,* Yakama Res. Assoc. 185–187, Yanadani Village (*in* Japanese).

IVES, R.L., 1948 : Plunge pools, potholes and related features. *Rocks and Minerals,* v. 23, no. 1, 3–10.

JEFFREYS, Harold, 1929 : On the transverse circulation in streams. *Proc. Cambridge Phil. Soc.*, v. 25, 2–25.

JOHNSSON, G., 1956 : Glacialmorfologiska studier i Södra Sverige med särskild hänsyn till glaciala riktninselement och periglaciala frostfenomen. *Medd. fr. Lunds Univ. Geogr. Inst.*, Avh. 30, 407p.

JORSTAD, F.A., 1961 : Pohtoles in boulders and in cohesive soils. *Norsk. Geogr. Tidskr.*, v. 18, Oslo 1961–1962, 144–155.

KAGAMI, A., 1978 : Origin of place Names. *Japanese Language,* v. 12, 381–409, Iwanami, Tokyo (*in* Japanese).

KALM, P., 1742 : Om de sa kallde Berg-eller Jattegrytor i Bohus Län ; *Kgl. Svenska Vetenskaps-Akad. Handl.*, v. 3, 122.

KASHIMA, N., 1984 : Potholes in the Kurokawa River (downstream from Yakama). *Res. Rept. "Yakama Potholes", Special Natural Monument,* Yakama Res. Assoc., 89–96, Yanadani Village (*in* Japanese).

KASHIMA, N., TAKAHASHI, J., SATO, S., and HAYAMI, T., 1984 : Geology of the Kurokawa River region. *Ibid.*, 21–50 with geological map, 1/10,000 (*in* Japanese).

KAUFMANN, W., 1931 : *Angewandte Hydromechanik* I. Berlin.

KELLY, R.W., WOOD, G. M., MARMAN, H. V., and MILICH, J.J., 1963 : Rotating disk apparatus for cavitation damage studies in high temperature liquid metal. *ASME paper 63-AHGT-26.*

KINGSBURY, J.W., 1952 : Pothole erosion on the western part of Molokai Island, Territory of Hawaii. *Jour. Soil and Water Conserv.*, v. 7, no. 4, 197–198.

KNAPP, R.T., and HOLLANDER, A., 1948 : Laboratory investigation of the mechanism of cavitation. *Trans. Amer. Soc. Mech. Eng.*, v. 70. 418–435.

KNAPP, R.T., 1952 : Cavitation mechanics and its relation to the design of hydraulic equipment. *Proc. Inst. Mech. Eng.*, v. 166, 150–163.

KODAMA, Y., and IKEDA, H., 1984 : Experimental study on the formation of "Yakama Potholes". *Res. Rept. "Yakama Potholes", Special Natural Monument,* Yakama Res. Assoc., 154–164, Yanadani Village (*in* Japanese).

KOKUBU, N., 1941 : A new example of pothole erosion in the hills of Taiho-Syo, Tainan prefecture. *Taiwan Tigaku Kizi,* v. 12, no. 2–3, 17–21 (*in* Japanese).

KRÜMMEL, O., 1907 : *Handbuch der Ozeanographie.* Stuttgart.

KUHM, H.W., 1954 : Glacial potholes in Minnesota and Wisconsin. *Earth Sci. Digest,* v. 7, no. 7, 13–14.

LAMB, H., 1932 : *Hydrodynamics.* 6th ed. Cambridge.

LEE, J.S., 1922 : Notes on traces of recent ice-action in northern China. *Geol. Mag.*, v. 59, no. 691, 14–21.

LEE, J.S., 1933 : Quaternary glaciation in the Yangtze Valley. *Bull. Geol. Soc. China,* v. 13, no. 1, 15–62.

LEE, J.S., 1934 : Data relating to the study of the problem of glaciation in the lower Yangtze Valley. *Ibid.*, v. 13, no. 3, 395–432.

LEE, J.S., 1936 : Confirmatory evidence of Pleistocene glaciation from the Huangshan, southern Anhui. *Ibid.*, v. 15, no. 3.

LEE, J.S., 1937 : Lushan in glacier stage. *Bull. Geol. Central Acad.* (*in* Chinese).

LEE, J.S., 1975 : *Quaternary glacier in China.* Science Press, Peking, 160p. (*in* Chinese).

LELIAVSKY, S.L., 1966 : *An introduction to fluvial hydraulics.* N.Y. Dover Publ., 257p.

LICHTMAN, J.Z. and WEINGRAM, E.R., 1964 : The use of a rotating disk apparatus in determining cavitation erosion resistance of materials. HOLL, J. W. and WOOD, G. M., ed. *Symposium on Cavitation Research Facilities and Techniques, 185–196, New York.*

LJUNGNER, Erik, 1930 : Spaltentektonik und Morphologie der schwedishen Skagerrak-Küste. *Bull. Geol. Inst. Univ. Uppsala,* v. 21, 255–478.

LOGAN, M.H., 1959 : Field trip report to Prineville Dam, Sept. 8–11, 1959. *U.S.Bur. Reclamation Geology open-file rept.*, Denver.

LOUGEE, R.J., 1946 : Time measurements of pothole development at Westfield, Mass. *Bull. Geol. Soc. Amer.*, v. 57, no. 12, pt. 2, 1282–1283.

LUGEON, Maurice, 1925 : Sur le surcreusement fluvial, Exemple du Rio Negro d'Uruguay. Note 2 de *M. Comp. Rend. Acad. Sci.*, no. 180, 180–183.

MANNING, P.C., 1901 : Glacial potholes in Maine. *Proc. Portland Soc. Nat. Hist.*, v. 11, pt. 5, 190

MARR, J.E., 1926 : The Kailpot, Ullswater. *Geol. Mag.*, v. 63, 338–341.

MASUTOMI, H., 1949 : The potholes of Ufigawa. *Minerals and Geology*, no. 3, 18 (*in* Japanese).

MATSUURA, H., MIYAZAKI, M., and SATO, S., 1985 : Origin of Yakama Potholes in Yanadani Village, Ehime—eddy theory and cavitation theory. *Abst. Papers 92 Ann. Meet., Geol. Soc. Japan*, 51 (*in* Japanese).

MCKELLAR, P., 1890 : Potholes north of Lake Superior. *Bull. Geol. Soc. Amer.*, v. 1, 568.

MIYAZAKI, M., and MATSUURA, H., 1984 : Yakama potholes in Yanadani Village, Kamiukena County. *Nat. Ehime*, v. 26, no. 6, 11–12 (*in* Japanese).

MIYAZAKI, M., 1984 : Potholes in Yanadani Village. *MS of Graduate Thesis, Fac. Educ., Ehime Univ.* (*in* Japanese).

NAGAI, H., 1954 : *New interpretation of Yakama Potholes.* MS (*in* Japanese).

NAGAI, K., and HAGA, K., 1984 : Topography of the Kurokawa River region. *Res. Rept. "Yakama Potholes", Special Natural Monument*, Yakama Res. Assoc., 1–20, Yanadani Village (*in* Japanese).

NAKAYAMA, M., and SAKAMOTO, T., 1973 : Potholes along the Arakawa River. *Mem. Fac. Educ. Saitama Univ.*, Math. and Nat. Sci., no. 27, 45–53 (*in* Japanese).

NAOKI, J., 1983 : Geology of Yanadani Village, Ehime Prefecture. *MS of Graduate Thesis, Fac. Educ. Ehime Univ.* (*in* Japanese).

NOHARA, M., TSUCHIYA, R., and YAMAJI, H., 1983 : Potholes at Kibado Sea Shore, northwestern Yamaguchi Prefecture. *Abst. Papers Ann. Meet. Geogr. Soc. Japan* (*in* Japanese).

NOWOTNY, H., 1942 : Materials destruction through cavitation tests carried out with high frequency oscillator. Berlin, *Vereines deutscher ingenieure*, Translation by Ferd Stenger, 1948, U.S.Bur. Reclam. Tech. Library, Denver.

OGAWA, T., 1932 : On the Pleistocene glaciation in central Japan. *Proc. Imp. Acad.*, v. 8, no. 1, 16–19.

OGAWA, T., 1933 : On a type of glacial topography in the northern foothills of Tateshina-yama, Shinano Province. *Ibid.*, v. 9, no. 5, 211–214.

OKAMOTO, Y., 1972 : Piedmont glaciation in the Taiga forests in Ice Ages in Japan and northern Italy similar to those now present in southern Alaska. *24th IGC, Sec. 12, Quat. Geol.* 175–186.

OSTWALD, W., 1934 : Über anomale Turbulenz bei Sohlen. *Kolloid-Zeitschr.* Bd. 68, 211–226.

PENK, Albrecht, 1894 : *Morphologie der Erdoberfläche,* Ⅰ , Ⅱ . Stuttgart.

QUATERNARY GLACIER and GEOLOGY COMMITTEE, GEOL. SOC. CHINA, 1982 : Achievement and view of Quaternary glacier and geology in China. *Geol. Rev.*, v. 28, no. 6, 581–585 (*in* Chinese).

QUIRKE, T.T., 1925 : Potholes and certain features of glacial abrasion. *Trans. Illinois State Acad. Sci.*, v. 17.

RASMUSSEN, R.E.H., 1949 : Experiments on flow with cavitation in water mixed with air. *Trns. Danish Acad. Tech. Sci.*, v. 1, 1–63.

REHBOCK, Th., 1928 : Abfluss, Bettbildung und Energiehaushalt der Wasserläufe. *Verhandl. Wissenschaftl. Abhand.* 22 Deutschen Geogr. Karlsruhe 7 bis 9, 1927, Breslau.

REYNOLDS, Osborne, 1894 : Experiments showing the boiling of water in an open tube at ordinary temperatures. *Papers on mech. and physic. subj.*, v. 2, Cambridge, 1901.

RILEY, C., 1942 : Glacial potholes on Outpost Island, Great Slave Lake, NW territories. *Jour. Geol.*, v. 51, no. 4, 270–275.

ROSBERG, J.E., 1925 : Jättgrytor i södra Finland. *Fennia*, Bd. 46, Nr. 1, Helsingfors.

ROUSE, H., 1950 : *Elementary fluid mechanics.* John Wiley & Sons, N.Y.

RUTENBECK, Theo, 1941 : Über Werkstoffzerstörung dürch Kavitation am Schwinggerät. *Zeitschr.*

Metallkunde, jahrg. 33, 145-152.

SALOMOM, W., 1926 : Die Rehbockschen Wasserwalzen und ihre Bedeutung für die Evorsion und Akkumulation. *Geol. Rundschau*, Bd. 17,

SATO, D., 1919 : On the origin of potholes. *Geogr. Magaz.*, no. 31, 185-191 (*in* Japanese).

SATO, D., 1927 : Oze Potholes at Seki, Shimo-shonai Town, Miyazaki Prefecture. *Res. Rept. Natural Monument, pt. of Geol. Mine.*, no. 2 (*in* Japanese).

SATO, S., and HAYAMI, T., 1983 : Preliminary report of potholes in the Kurokawa River (upstream from Yakama). *Prelim. Rept. Yakama Res. Assoc.*, Yanadani Village (*in* Japanese).

SATO, S., 1984 : Pohtoles in the Kurokawa River (upstream from Yakama). *Res. Rept. "Yakama Potholes", Special Natural Monument*, Yakama Res. Assoc., 51-88, Yanadani Village (*in* Japanese).

SATO, S., and HAYAMI, T., 1984 : Origin of potholes and bearing of pothole research. *Ibid.* 171-184 (*in* Japanese).

SATO, S., 1986 : Regional geology in Huili district, Sichuan Province. *Geology of the Panxi Region, Sichuan Province, Southwest China. in* Matsumoto, Y. and Kano, T. *ed.* Rept. 1983, 1984 Cooperative Res. Japan and China, 71-75, Yamaguchi Univ.

SAWAMURA, T., 1966 : Ide Potholes in the Matsuda River (designated Kochi Prefecture). *Chigaku Kenkyu*, no. 17, 10-17, Kyoto (*in* Japanese).

SCHREIBER, J.F.Jr., 1949 : Geologic sketches—potholes. *Maryland Natural.*, v. 19, 48.

SCHRÖTER, H., 1933 : Korrosion bei Kavitation. *Z.d. Vereins Deutsch Ing.*, Bd. 77, 865-869.

SCHRÖTER, H., 1934 : Metallographische Unters z. Frage d. Kavitationszerstörung. *Ibid.*, Bd. 78, 1161-1162.

SHALNEV, K.K., 1957 : Experimental Study of the Intensity of Erosion due to Cavitation. 22 in *Cavitation in Hydrodynamics*. Phil. Lib., N.Y., 1-37.

SHEPHERD, R.G., 1972 : A model study of river incision (MS thesis) Fort Collins, *Colorado State Univ.*, 135p.

SHEPHERD, R.G., and SCHUMM, S.A., 1974 : Experimental Study of River Incision. *Bull. Geol. Soc. Amer.*, v. 85, 257-268.

SIMPSON, E., 1935 : Note on the formation of the Yorkshire caves and potholes. *Proc. Spelaeol. Soc.*, v. 4, no. 3, 224-232.

SPENCER, J.W.W., 1908 : Soundings in Niagara and under the Falls. *Sci. Amer.*, no. 99, 76-77.

SPITZNAS, R.L., 1950 : Potholes and channel scrolls in the Nanajo sandstone, Zion National Park. *Earth Sci. Digest*, v. 5, 3-6.

STAMP, L.D., 1940 : The Irrawaddy River. *Geogr. Jour.*, v. XCV no. 5, 329-356.

STANLEY, G.M., 1934 : Pleistocene potholes in the Cloche Mountains of Ontario. *Michigan Papers in Geogr.*, no. 4,

STEFANIAK, H., 1961 : Hypothese zur Entstehung der Fischbacher Gletscherrinnen. *in* Fehn, H. *ed. Der Gletscherschliff von Fischbach am Inn*. Landeskundl. Forschung., H. 40,

STONE, G.H., 1899 : The glacial gravels of Maine and their associated deposits. *Mon. U.S. Geol. Surv.*, no. 34, 324.

STREIFF-BECKER, R., 1951 : Potholes and glacier mills. *Jour. Glaciology*, vo. 1, 488-490.

SVENONIUS, F., 1918 : Nagra bidrag till jattegrytornas morfologi och forekomstsatt. *Geol. Förening. i Stockholm Forrhandl.* Bd. 40.

Symposium, 1947 : Cavitation in hydraulic structures : a symposium. *Trans. Amer. Soc. Civil Eng.*, v. 112, 1-124.

TABUCHI, H., and URUSHIBARA, K., 1971 : Climatic change in the Quaternary in Asia. *in* YOSHINO, M., *ed. Water Balance of Monsoon Asia.*

TAKAI, T., 1984 : Geology of the Kurokawa River region. *MS of Graduate Thesis, Fac. Educ., Ehime Univ.* (*in* Japanese).

TANABE, K., 1941 : Some potholes in sea erosion, especially formation condition in So-okitsu and Enoshima. *Geogr. Rev. Japan*, v. 12, no. 11, 938-943 (*in* Japanese).

TANABE, K., 1941 : Marine potholes. *Ibid.*, v. 17, 938-944 (*in* Japanese).

THABERG, C., 1922 : Lokal med recenta jattegrytor i Motalastrom. *Geol. Forening. i Stockholm Forhand.* Bd. 44, 740.

TOKUDA, T., 1918 : Some types of river erosion. *Jour. Geol. Soc. Japan*, no. 27, 293 (*in* Japanese).

TOKUDA, T., 1937 : Pothole in sea erosion. *Geogr.*, v. 5, no. 3, 19–22 (*in* Japanese).

TOKUSHIGE, E., 1936 : Geological significance of Ogi Sea Shore. *Res. Rept. of Natural Monument in Niigata Pref.* no. 6 (*in* Japanese).

TOKUSHIGE, E., 1939 : Development history of Ogi Sea Shore, Sado Island in Recent (Holocene). *Geogr. Rev. Japan*, v. 15, no. 15, 803–804 (*in* Japanese).

TRICART, M.J., 1959 : Observations sur le faconnemont des rapides rivers intertropicales. *Imprimerie nationale*, 289–313, Paris.

TSCHANG, H.L., 1962 : Some geomorphological observations in the region of Tampin, S. Malaya. *Zeitschr. Geomor.*, v. 6, no. 3/4, 253–259.

TSCHANG, Hsi-lin, 1958 : Potholes in the river beds of north Taiwan. *Erdkunde, Archiv wissenschaftl. Geogr.*, Bd. 11, Lfg. 4, 297–303.

TSCHANG, Hsi-lin, 1964 : The fluvial potholes of Hong Kong. *The Chung Chi Jour.* v. 3, no. 2, 118–131.

UDDEN, J.A., 1925 : Etched potholes. *Bull. Texas Univ.*, 2509.

UNDAS, I., 1963 : Ra-morenen i Vest-Norge. *J. W. Eides* Forlag., Bergen.

UPHAM, W., 1900 : Giants' kettles eroded by moulin torrents. *Bull. Geol. Soc. Amer.*, v. 12, 25–44.

VELIKANOW, M.A., 1957 : Krupnomasstabnaja turbulentnost' i struktura ruslovogo presessa. *Izv. Akad. Nauk, SSSR, Ser. geofiz.* I, 71–78.

VENNARD, J.L., and LOMAX, C.C.Jr., 1950 : *Experimental research on cavitation collapse pressures*. Stanford Univ., Calif.

VIRIEUX, A., 1934 : Lew marmites d'erosion, contribution a l'etude de leur formation, d'apres des observations faiters en Suisse et en Egypte. *Bull. Inst. Egypte*, t. 16, f. 2, 167–176.

VON POST, 1866 : Bidrag til Jattegrytornas Kannedom. *Oefvers. af Kgl. Vetensk.-Akademiens Forhandl.*

WAKIMIZU, T., 1909 : Nezame-notoko, Kiso Valley. *Geogr. Mag.*, no. 12, 252 (*in* Japanese).

WATANABE, K., KATSURA, Y., HOMMA, H., HISADA, K., KODAMA, Y., and IKEDA, H., 1984 : Yakama Potholes. *Res. Rept. "Yakama Potholes", Special Natural Monument*, Yakama Res. Assoc., 97–166, Yanadani Village (*in* Japanese).

WICHDORFF, H.V., 1916 : Über Strüdellocher im Flussbett der Schearza Thuringen und ihre gegenwärtige Entstehung. *Jahrb. Konigl. Preussischen Geol. Landan.* Berlin, Bd. 35, Teil 2, 271.

YAGI, S., 1956 : Potholes at Yakama. *Nature of Ehime*, 3, 60–63, Sci. Educ. Assoc. Ehime Pref. (*in* Japanese).

YAGI, T., 1934 : On a probable glacial deposit at Iriya in Kitakami Mountains. *Proc. Imp. Acad.*, v. 10, no. 3, 173–176.

YAKAMA RESEARCH ASSOCIATION, 1984 : *Research report of "Yakama Potholes", Special Natural Monument.* 187p., Yanadani Village (*in* Japanese).

ZHU, Kezhen, 1973 : Preliminary study of climate change in recent five thousands years in China. *Sci. Sinica*,no. 2, 168–189, Peking.