The Rifling of Diamond-Drill Cores

BY WALTER R. CRANE,* PH. D., STATE COLLEGE, PA.

(Arizona Meeting, September, 1915)

OPERATORS of diamond drills have long been familiar with thread-like markings or riflings on cores but apparently have given but little serious thought to the conditions that are responsible for their production. The opinion generally held by those who have observed the phenomena is that the riflings are produced directly or indirectly by vibration, but so far as the writer is aware no systematic attempt has been made to demonstrate the fact.

A careful search through the literature on diamond-drilling practice has been rewarded by only one reference to such markings of cores. J. N. Justice[1] writes, "Of the peculiarities met with in the core, I will mention only one. The core from the "H" drill, at about 360 ft. came out rifled and pentagonal. The change from the circular to the pentagonal was sudden, and for 9 ft. this structure was maintained, when suddenly it returned to the circular. I have not been able to find any one who can explain the cause of this change of form. The drill men marveled at it and suggested vibration, six-stone bits, and several other hypotheses which need not be mentioned."

The writer became interested in the matter of core riflings some 10 years ago while in the Flat River lead region of Missouri, where many remarkable examples of "rifled" cores were observed and collected. Since that time similar phenomena have been observed in various localities throughout the United States and Canada, and samples have been gotten together illustrating a large number of variations in form.

After a careful study had been made of the material at hand it seemed desirable that certain data should be obtained from the experience of others regarding the normal action of diamond drills in forming cores, portions of which are occasionally rifled, before an attempt was made to draw any conclusions as to their cause.

About 20 letters were addressed to diamond-drill companies, operators, and engineers actively engaged in drilling operations, with a

---

* Dean of the School of Mines, The Pennsylvania State College.

[1] J. N. Justice: Diamond Drilling in West Africa, *Transactions of the Institution of Mining and Metallurgy*, vol. 12, p. 309 (1902–3).

request for a statement of their opinion concerning the cause of systematic markings or rifling of cores. The concensus of opinion obtained from the replies received was that vibration is responsible for the phenomena. In a general way vibration seems to be the only logical explanation, yet owing to the fact that in the operation of drilling, spiral markings on cores are the exception rather than the rule (although in certain formations they are of frequent occurrence), it has not been easy to determine the exact relation existing between vibration and the markings.

The character of phenomena observed on examination of a large number of rifled cores may be summarized under their respective heads in the following paragraphs.

Number of Riflings to the Turn

While the markings are commonly spoken of as riflings, it might be better to designate them as threads, owing to their association with other terms. The number of threads to the turn varies between wide limits; the smallest number observed was three (No. 3, Fig. 1), the largest 13—the average being seven. Five threads to the turn appear to be the most common, although that may be a mere coincidence as a result of examining a comparatively large number of cores from one district, where similar formations were drilled through, and under like conditions of drilling, particularly with respect to equipment. With large pitches the five-threaded riflings may assume a pentagonal section and are commonly spoken of as "pentagonal" cores.

While the number of threads was observed to be uneven in every core examined, yet it has been demonstrated that there may be even numbers as well. In fact, there may be both odd and even numbers of threads on one and the same core, although on the samples examined change in number was brought about by threads bifurcating or coälescing, thus maintaining the relation as to number. Further, it seems to be the rule that prominence of threads is coincident with a diminution in number (Nos. 3 and 8, Fig. 1).

Pitch of Threads

The pitch of threads noted on a large number of cores varies even more than does the number of threads to the turn; the range observed was between 7/16 in. (for nine-threaded core) and 3 5/8 in. (for five-threaded core). A much wider range is possible, and, in fact, no limit can be set. The pitch of threads varies directly, of course, with the number of threads to the unit length or inch. The smooth or unrifled core may be considered as the lower limit (lower end of No. 5, Fig. 1), the threads blending one into the other; the strongly rifled form with pitch approaching infinity is the upper limit, both limits being common but not so universal as the intermediate forms (see Nos. 1, 3, and 8, Fig. 1). Further, there is a definite relation between the number of threads to the turn and the pitch.

Depth and Shape of Threads

The depth and shape of threads are concordant characteristics of rifled cores and while they may be more difficult to explain than some of the other features, they are even more clearly defined. The depths of threads as measured vary between $\frac{1}{100}$ and $\frac{1}{16}$ in. apparently varying

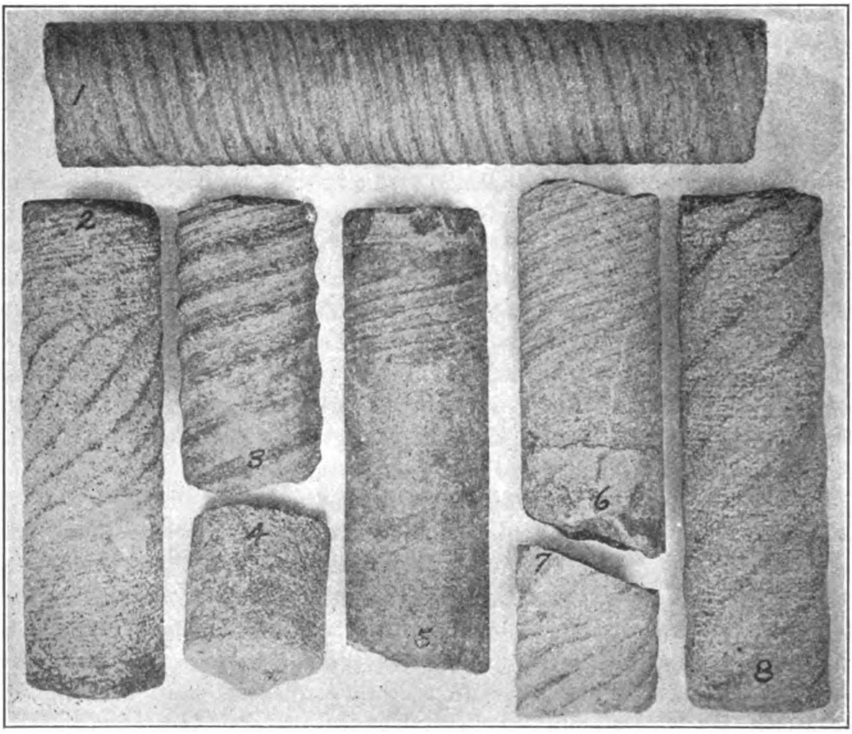

FIG. 1.—SAMPLES OF CORES IN LIMESTONE SHOWING RIFLINGS.

to a limited degree with the number of threads to the turn, as mentioned above.

The shape may be of a variety of forms, the rounded form predominating in the coarser threads (No. 3, Fig. 1), while roughly V-shaped threads occur when the riflings and pitch are small (see ends of No. 2, Fig. 1). A braided appearance is occasionally observed, due to a set of threads of a certain pitch being superimposed upon another of different pitch (see No. 6, Fig. 1 and Fig. 2). It is not of infrequent occurrence that double and triple threads are observed which in all respects are similar to the ordinary forms; however, with such combinations the troughs between the riflings are usually wide and shallow (see Fig. 3). Flat-topped or square threads are also formed.

Various reasons and theories have been advanced to explain the formation of threads on diamond-drill cores, the following being the most commonly held: (1) vibration of drill rods; (2) four- and six-stone bits; (3) the up-and-down action of water currents carrying cuttings; (4) particles of mineral or metal working their way down through the core barrel; (5) differential action between core and core barrel, the former having been broken off and turned through friction with revolving bit and core barrel; and (6) overset of stones in bit.

After careful investigation and consideration of the data at hand, certain of the causes outlined above may be eliminated as inadequate, thus narrowing them down to one or more possible or probable ones.

It is but natural to expect that machines operating under high

Fig. 2.—Braided Markings on Core Due to Two Sets of Threads Crossing One Another. (Rub of Core.)

pressure, as diamond drills do, will set up considerable vibration, particularly when boring through difficult formations. So intense is the vibration of the drill and rods at times that the whole outfit and even the ground for many feet around will be strongly shaken. Vibration is therefore a well-known phenomenon attendant upon diamond drilling and its presence does not have to be assumed.

Water currents laden with cuttings do not, except very rarely, as when reversed, enter the core barrel or in fact the inside of the bit, as the wash water passes from the inside to the outside of the bit, and thence to the surface between the drill rod and the hole or casing. Therefore, during the operation of drilling only practically clear water comes into contact with the core.

The theory advanced that the number of stones (carbons) in the bit is responsible for the riflings on cores can hardly be considered as sound for the reason that bits with four, six, or eight stones (considering the inside stones only) seldom if ever produce a number of threads corresponding to the number of stones; in fact, in all cases observed the threads were odd numbers. Further, as the stones are evenly spaced about the bit, it is obvious that the number of threads would be determined by the number of stones and that the number could not change either by an increase or decrease, odd or even. It would probably be more logical to assume that there is but one cutting point instead of a number.

What the effect of small particles of mineral detached from the core and pieces of metal broken from threaded connections of rods, teeth of clutches at the surface, etc., may be when they enter the rod and are carried to the core barrel and bit by wash water, is largely conjectural except in those cases where cores have been jambed in bits and core

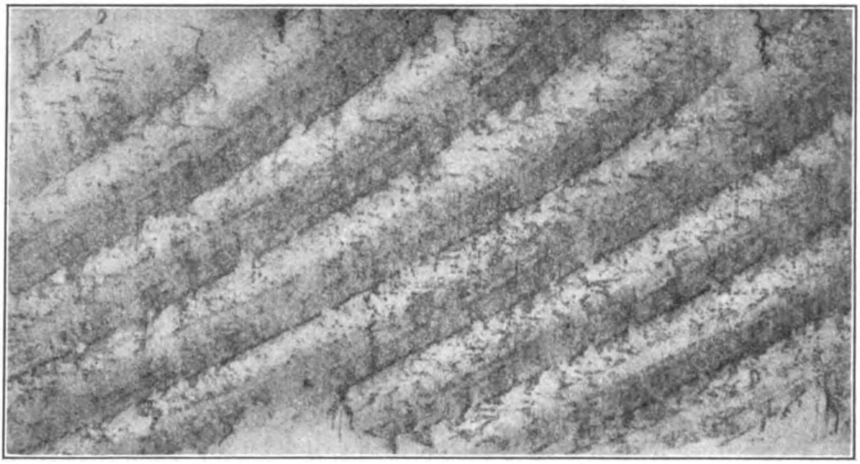

Fig. 3.—Riflings Showing Triple Threads and Lack of Parallelism Due to Changing Pitch. (Rub of Core.)

lifters by such fragments, or where the bit or core barrel has been severed by the cutting action of a particle lodged in the core. As pointed out above, it might be more reasonable to assume that one cutting point is responsible for the riflings, which condition could be brought about by a particle of hard mineral or a fragment of steel lodging in the core lifter or bit and acting as the cutting medium.

The overset of stones in a bit is so slight that it would hardly seem possible for threads to be cut to the depths observed, unless it is assumed that through accident a stone has become loosened and the overset greatly increased. The usual overset of stones in bits is $1/64$ to $1/32$ in., while the depth of threads may reach and even exceed $1/16$ in. It is difficult to imagine any possible movement of bit that would allow a stone normally set to cut to that depth. It is reasonable then to assume that particles of mineral, fragments of metal or loosened diamonds may be the media by which the threads are cut.

The breaking off of the core and its rotation within the core barrel is of common occurrence and can be observed in parts of nearly every section of core lifted, especially in certain loosely bedded or broken formations. That the wear of the loosened portions of core is great is evident on comparing the actual advance of rod with the length of core extracted (see No. 4, Fig. 1). Further, it is a curious coincidence that practically every case of rifled core examined bore evidence of considerable wear on one or both ends, showing that the cores had been free to rotate with the core barrel, but had been retarded to a certain extent by grinding between the over and underlying portions. That differential action should be sufficiently positive and regular to permit of well-defined and symmetrical markings is exceedingly doubtful.

It is evident from the foregoing statements that of the possible causes there are only two that have sufficient weight and prominence to be considered worthy of further consideration, namely: vibration and the cutting action of particles of mineral or metal lodging in the bit or core barrel, or the excessive overset of loosened stones in the bits. As it is necessary to have a cutting medium whether it be mineral, metal, or overset of diamonds, we can assume that the latter conjecture is more or less tenable. The cutting medium tentatively agreed upon, the formation of the threads resolves itself into the question of how vibration might act to produce such phenomena.

Certain observed facts seem to be opposed to the theory of vibration of drill rod as a probable cause of riflings; however, as the actual conditions existing at the time of the formation of the markings are not definitely known, some of the points mentioned below may have no great weight.

The facts that do not seem to conform with the theory of vibration as a cause of riflings on diamond-drill cores are as follows: (1) rifled cores occur more frequently in soft than hard formation, where the resistance to rotation of the drill rods and the consequent vibration of rods might be expected to be the least; (2) contact with sides of the hole, particularly inclined and crooked holes, would prevent to a large extent the free longitudinal or transverse vibration of the rods; and (3) an apparent persistence in number of threads, whether odd or even, regardless of depth of hole, size of rods, speed of advance, etc.

On the other hand, the facts supporting the theory that vibration is responsible for rifling of cores may be outlined as follows: (1) regularity of threads, the same relation existing between threads of different pitch (see No. 2, Fig. 1, and Fig. 4); (2) the number of threads to the turn is remarkably persistent and when an increase or reduction occurs the change is due to the splitting up or blending of existing threads (see Fig.

5); (3) the distance between threads circumferentially remains constant (see No. 2, Fig. 1 and Fig. 4); (4) the threads show that they are cut by some positively and systematically acting medium moving circumferentially, and not by water currents or a grinding action parallel with the threads; (5) the crossing of threads of different pitch, producing a braided effect (see No. 6, Fig. 1 and Fig. 2); (6) the rifling of cores is of more frequent occurrence in vertical holes or those of slight inclination; and (7) rifling is probably more common and pronounced in holes of considerable depth.

The two last-mentioned observations are largely conjectural, but from information at hand, though meager, the assumptions seem to be corroborated.

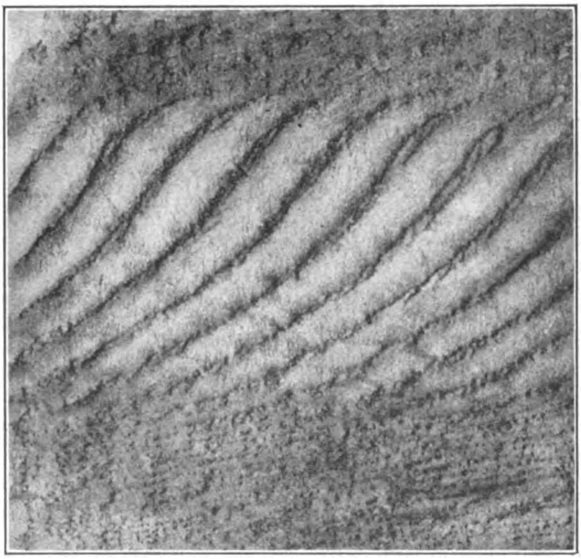

FIG. 4.—WIDE RANGE OF PITCH DUE TO VARIATIONS IN SPEED OF ROTATION. (RUB OF CORE.)

Up to this point the data were obtained from and based directly upon observations taken in the field and a careful examination of cores. While the evidence points very conclusively to the fact that vibration must be the cause of the riflings, yet what form the vibration takes, whether longitudinal or transverse, and the relation it bears to size of rods, rate of advance, revolutions per minute, etc., are wholly unknown. How to secure the information was the next question that had to be answered. It was not until the thought suggested itself that it might be possible to reproduce the riflings, that the solution assumed a tangible form.

A metal lathe was chosen as the most suitable instrument to be employed for investigating the formation of riflings or threads on cores, although no attempt was made to turn out cores from solid material.

Placing a piece of pipe in the chuck of the lathe with one end free, and the cutting tool set as short as possible to prevent vibration, an attempt was made to remove thin layers from the outside of the pipe with varying speeds of advance and rotation of the pipe. As the tool advanced toward the chuck from the free end of the pipe, vibration became more pronounced and finally very violent, being maintained up to the chuck. On examination of the surface of the pipe after such a cutting

FIG. 5.—CORE SHOWING THE SPLITTING UP AND BLENDING OF THREADS, ALSO SUDDEN CHANGE OF PITCH. (RUB OF CORE.)

had been made, it was found that rough threads had been formed, which closely resembled the riflings observed on the drill cores (see No. 5, Fig. 6).

With this as a beginning an elaborate series of experiments was made, during which a large number of combinations of speed of advance (advance in terms of threads per inch), speed of rotation, size and length of piece in chuck, shape and length of cutting tool, and character of material (both tubular and solid being used), were tried with the result that practically every form of rifling observed on the cores was obtained.

However, with the limitations necessarily placed on the work through size of lathe and test pieces, also speeds, it was not possible to reproduce the full range of threads as to number to the turn, pitch, etc. (see Fig. 6).

To conform still further to the conditions existing in drilling, the end of the test piece not in the chuck was rigidly supported by the tail piece of the lathe, thus holding the piece rigidly and under compression between the two points of support. No difference in results obtained was observed.

It is evident that in this work the conditions existing in the case of the diamond drill were reversed in that the part representing the core was

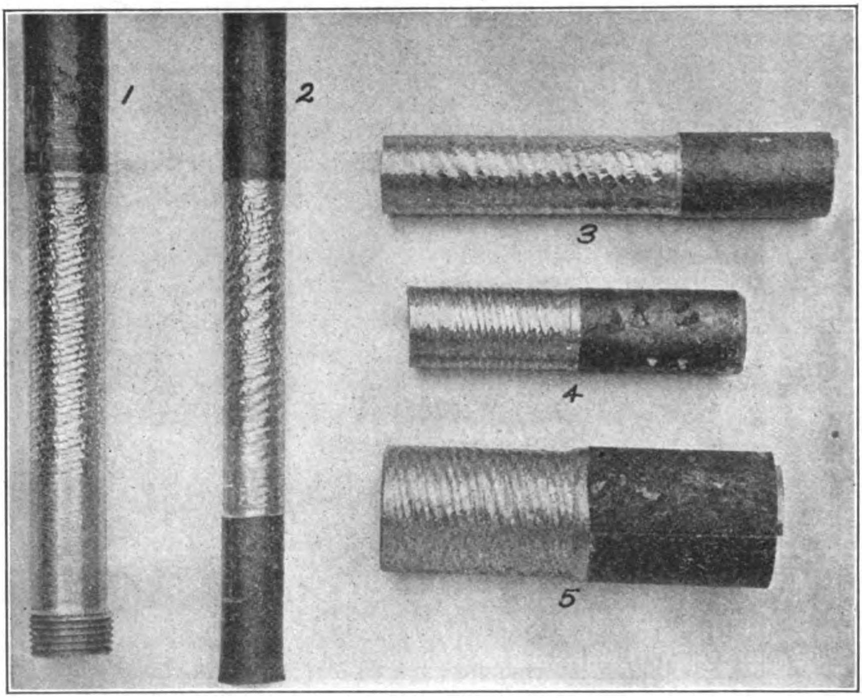

FIG. 6.—RIFLINGS FORMED ON METAL TUBES AND RODS BY VIBRATION.

rotated while the tool remained practically rigid. To verify the results further, a smooth diamond-drill core was substituted in place of the metal tube or rod and a long slender tool was used instead of the rigid one formerly employed. Rough but rather indistinct threads were produced, which although not entirely satisfactory still further confirmed the results previously obtained. Riflings were also produced on the inner surface of cylinders, a long cutter-bar being used, the vibration of which produced a peculiar frosted or wavy marking at slow speeds, but developed into distinct threads at higher speeds and greater vibration.

The action of a lathe when producing riflings or thread-like markings is commonly spoken of as "chattering" and in lathe work is very objectionable. When change in speed is not possible nor desirable other means are employed to dampen the vibration, a common method being to insert a wooden wedge between chuck and bed plate, which while not preventing rotation stops the vibration.

With the large amount of data obtained from this work it was possible to correlate it with information secured from the rifled cores and thus demonstrate in a conclusive way the cause of the riflings and the relation that exists between the number of threads, pitch, etc.

Conclusions

The phenomena of rifled cores are due to torsional vibration of the drill rods, which in turn is produced by the rotation of the rods. The

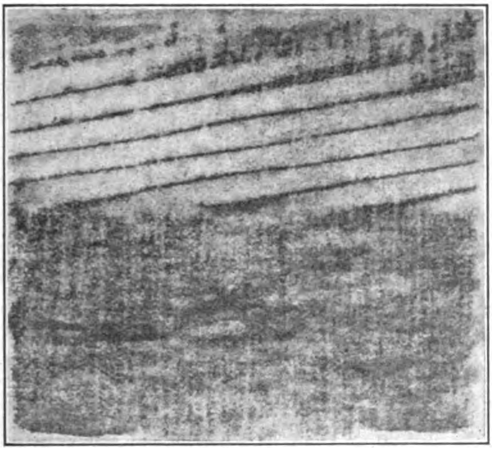

Fig. 7.—Abrupt Change from Smooth Core Below to Rifled Core Above. (Rub of Core.)

cutting medium attached to the rods engages with the core, penetrating to a certain depth, and thereby temporarily checking the rotation of the rods. When the energy stored up in the rods by the torsional strain exceeds the frictional resistance between the cutting medium and the core, it forces the cutting point out and the rod springs around until the strain is relieved, the action being repeated uniformly and indefinitely. The depth to which the cutting point enters the core depends upon its size, shape, and hardness, and upon the hardness of the core, also upon the intensity of the vibration. The distance through which the cutter rotates between points of contact with the core determines the number of threads to the turn, but it is probable that the number once established predisposes its regularity and symmetry. With lower speeds of rotation the vibration is less intense and the cutting point remains in contact with the core for a longer period; the number of threads to the turn as well as the pitch of the threads may be changed in this manner.

The distance between threads of like number measured circumferentially is constant, but by increasing the period of contact the pitch may be changed without altering the number (see Nos. 2 and 3, Fig. 1 and Figs. 3 and 4). The greater the period of contact, the greater is the distance between threads measured at right angles, thus producing lack of parallelism between threads (see Figs. 3 and 4). It may be said, then, that the greater the actual distance between threads the greater the pitch and, conversely, the less the distance the less the pitch.

There is nothing to indicate that rate of advance affects the formation of riflings or threads on cores except in so far as it may limit the length of core affected; nor does the size of the core have any appreciable effect (see Fig. 7).

The length of the line of rods should and may have some influence in so much as the torsional vibration is probably affected by it. However, no appreciable difference in vibration was noted in the work done, as the tool approached the chuck which held the test piece, the vibration maintaining its intensity until the tool reached the chuck.

The conclusions reached by the investigations outlined above may be briefly summarized as follows:

1. Riflings of cores are produced by torsional vibration of the rods.

2. The formation of multiple threads, or a number to the turn, is determined by the intensity of vibration, character of the cutting medium and the core.

3. The pitch of the threads is determined by speed of rotation of the rods.

4. The size and length of rods probably act only indirectly to modify the size, shape, and pitch of threads.

As rifling of core is produced by rotation and varies in prominence with the intensity of vibration, it is possible to prevent or very materially reduce the vibratory action of the drilling mechanism by reducing the speed of rotation of the rods. This method of procedure would undoubtedly be much less difficult and troublesome and far more efficacious than the practice of greasing the line of rods.

It is possible that aside from the desirability of knowing how rifled cores are formed, the knowledge may be of little or no importance, yet who can say when a purely scientific fact may not become of considerable economic value.

The writer is indebted to many persons engaged in the manufacture and operation of diamond drills for the interest shown in the investigations and the information freely given, and wishes in this connection to express his appreciation of the assistance rendered.

Discussion

H. M. Roberts, Minneapolis, Minn. (communication to the Secretary*).—The rifling of drill cores is a frequent source of interest to men engaged in diamond drilling. Previous to the appearance of Dr. Crane's paper, there has been little record of connected observation or rigid speculation as applied to the cause of rifling. Replying to one of Dr. Crane's letters of inquiry, I ventured my opinion that the cause of rifling was a complex problem in physics, which I had not attempted to solve up to that time, except to ascribe it to the general cause of rotation and vibration of the rods. The question is worth attention not only as a matter of curious scientific interest but also for the reason that it stimulates thought on the mechanical action which takes place at the end of a diamond bit. In discussing Dr. Crane's paper, I still recognize the complexity of the problem and merely note a few observations of fact with the inferences which may be drawn from them. I am indebted for suggestions from W. J. Mead, F. F. Fredlund and James W. Hunter among others on the staff of the E. J. Longyear Co.

It seems clear that the cutting medium which causes uniform threading must be the diamond bit itself. The deep, regular rifling of such dense rocks as granite and norite for long intervals admits of no other reasonable assumption.

Rifling occurs in many different rocks, both hard and soft, but in all instances noted there is one feature in common: the rock is homogeneous over the extent of the rifling.

Wall of Drill Hole Rifled

The wall of the drill hole itself is rifled, as well as the core. This has been observed in the shaft of the Isabella Mine in Northern Michigan, which was sunk on a 2-in. hole in diabase.

Fig. 1 shows a specimen taken from the walls of this hole. It is reasonable to suppose, therefore, that rifling of the core is also accompanied in most instances by rifling of the wall of the hole. This leads to the inference that perhaps the immediate end of the bit is responsible.

The Diamond Bit

A consideration of the great pressures which bear upon a bit during the drilling makes it quite certain that all the stones work and engage the rock together. Examination of a worn bit shows that all the stones have played their part. In this connection it is of interest to note that

* Received June 24, 1916

while diamond setters place outside stones very accurately to gage, they seldom use a gage in setting inside stones, which perhaps admits of one stone working alone on the inside for some interval of time. Those portions of the stones which project from the immediate interior and

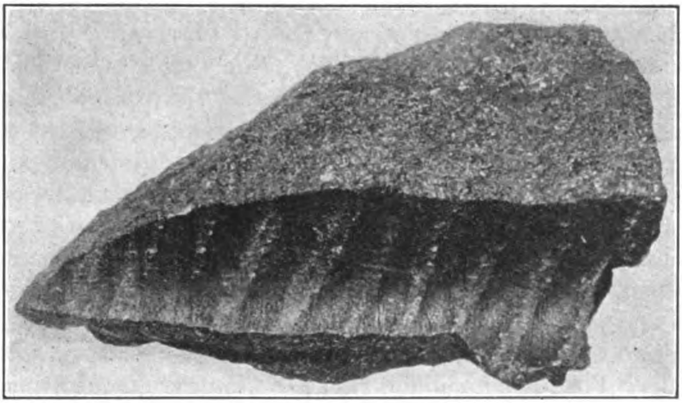

Fig. 1.—Specimen from Shaft of Isabella Mine, Cascade Range, Mich., Showing Rifling on the Wall of an "N" Drill Hole.

exterior edges of the face of the bit are no doubt responsible for the threading. It is apparent that any play in the bit would act with greatest effect at the extreme edges and would permit of greater penetration than the overset of that portion of the stone which extends up from the

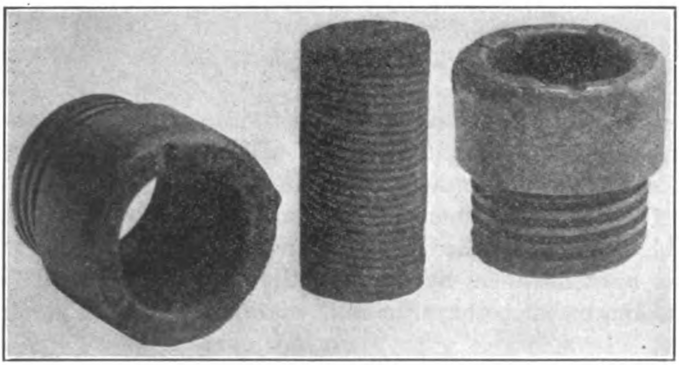

Fig. 2.—Worn Diamond Bits Which Have Produced Rifled Core and a Specimen of Quartzite Core Showing Left-Hand Threads. This Core Was Produced by a Bit Revolving to the Right.

edge on the inside and outside of the bit. During the drilling operation the protuberance of the stones at the edges is much greater than when first set up, owing to the wearing away of the metal. Fig. 2 shows two worn diamond bits which have produced rifled core. There is no evidence to show that a bit which has produced rifling was different in any material respect when first introduced to the hole than a bit which has produced smooth core. There is decided evidence to the effect that carbon wear and loss of metal are increased in any bit which has produced rifling. Thus the cause of rifling must lie in some force which acted upon the bit during the time when the rifled core was produced and which did not act during the time when the smooth core was produced.

Different Kinds of Threads and Varying Conditions

The depth of the hole does not seem to be a governing factor. Deeply rifled cores have been found in norite drilled with a 2-in. bit 10 ft. from the machine. Threads of different size, different pitch, and of varying numbers to the turn are to be found on cores of the same material from one hole drilled with the same bit and with the machine making the same number of revolutions per inch of advance in the bit. The threads are both left hand and right hand, although as far as my observation goes right-hand threads predominate. Fig. 1, showing the rifled wall of a drill hole, reveals both left-hand and right-hand threads in the same specimen. The bit producing these threads revolved to the right. I have counted both even and odd numbers of threads, varying from three to twenty, after which they become too fine to count; in fact, a smooth core always shows small variations from a true cylindrical shape.

Vibration of Rods Prevalent When Rifled Core is Produced

It is an observed fact that vibration of the rods is prevalent in drilling formations where regular rifling occurs. This obvious relation led to the replies which drill operators gave to Dr. Crane's question. The production of threads on a vibrating pipe in a lathe bears a distinct analogy and renders the relation between the vibration of the drill rods and rifling of the core quite certain. Let us examine this relation further, since we are pursuing the inquiry largely as a matter of pure interest.

Harmonic Motion of the Bit

The presence of threads over any interval of core indicates a constant play to and fro of the bit relative to the axis of the hole during its advance. Uniformity of the threading over any interval of core indicates that the swing of the bit operates according to some law. The fact that the number of threads and their character change from interval to interval, indicates that the factors causing the swing of the bit vary in considerable degree. We are evidently dealing with some type of harmonic motion. Possibly the homogeneous character of the rock found in most rifled cores is one of the principal factors which permits of harmonic motion in the bit. In considering the instance where many threads of low pitch appear on a cross-section of core, it is possible at first sight to conceive that the threads are due to spiraling which is directly proportional to the advance of the bit, but in an instance where corrugations of steep pitch are produced, as No. 8, Fig. 1, of Dr. Crane's paper, with perhaps 600 revolutions of the bit to an advance of 1 in., it is evident that the process is extremely complicated. The production of left-hand core by a bit revolving to the right is also a difficult matter to explain (see Fig. 2).

Consider the forces that operate on a flexible line of drill rods which are revolving rapidly. First, compression; second, torque. The play of these two forces sets up waves which have their lengths parallel but twisted with respect to the drill rods and with their crests and troughs at right angles to the axis of the hole. The twist in the rods is perhaps not as great as might be supposed, for when a bit is blocked under great pressure, and the engine is stopped and released, the chuck seldom revolves back more than a turn or a turn and a half. During this process the bit is presumably fast on bottom.

As the rods revolve, transverse waves advance down the rods at every azimuth, like waves of light. That waves of this type are produced is shown by the whipping out of uncased holes when drilling soft iron formation. The samples are often vitiated in this manner. Anyone who will climb the tripod and look down on the water-swivel when the rods are vibrating will see there a distorted but nevertheless fairly true picture of what is taking place at the bit on the other end of the rods. It is possible to count distinct beats in the play of the swivel to and fro as the rods vibrate.

The regularity of the grooving in the threaded core indicates that the waves producing it have a definite time interval with a fixed relation to the revolution of the rod. The fact that all the stones are working at the same time does not present any particular difficulty when it is remembered that in any one instance of threading the stones are always at fixed intervals with respect to the axis of the bit and therefore have a fixed relation to any wave that affects the bit and a fixed relation to the period of revolution. In the instance cited by Dr. Crane where pentagonal core is formed, the time of vibration must be nearly a definite divisor of the time of revolution. That is, during one revolution of the bit there were approximately five major wave motions which produced a portion of five threads on the core for a longitudinal distance of less than 1/100 in. In all other instances where the pitch is flatter the ratio must be more intricate. When right-handed threads are produced, the period of vibration is incommensurable and in this instance thereby deferred slightly each time with respect to the core as the rod revolves. When left-handed threads are produced, the period of vibration is also incommensurable, but in this case occurs just an instant earlier with respect to the core during each succeeding revolution.

Overtones

In wave motions of this kind it is conceivable that there are overtones; that is, if the period of one wave length be T, then there are wave lengths of $\frac{1}{2}T$, $\frac{1}{3}T$, etc. The braided threads on many pieces of core are suggestive of secondary action of this kind (see Fig. 2 of Dr. Crane's paper). All of the laws of resonance and interference in wave motion would enter into the amount of play in the bit as it revolves. Again, when relatively smooth core is produced, it is probably the result of the impact of countless numbers of periodic waves offsetting each other.

There are many other apparently simple phenomena in nature which are due to a combination of periodicities, as a beam of light or the general strike of a complexly folded iron formation.

The net result of the wave motions down the rods operating under the laws of resonance is translated into a wave whose length is nearly parallel to the circumference of the core and whose amplitude is along the radius, thus producing uniform threading. This is recorded in the rock like the mark on the indicator card of an engine. Only in rare instances do all the factors combine under the laws of resonance so that a deep definite tracing of the wave motion is formed.

Mathematical Interpretation

We may attempt to arrive at a rough mathematical interpretation of wave motion at the end of a diamond bit as expressed by threads in the core.

Let R = the number of revolutions of the bit during any interval of advance.

N = the number of threads appearing on the cross-section of core

$F(p)$ = some continuous or discontinuous function of the pitch of the threads, p having values from negative to positive infinity, $F(p)$ approaching the values -1 and $+1$ at these ends, and approaching the value zero as p approaches zero, the value of p being related to the value of N.

Let W = the number of major wave motions during any interval of advance of the bit, as indicated by the threads.

Then $W = R\,N\,F(p)$

Thus in the instance where pentagonal core is formed, and N equals 5, p approaches infinity and $F(p)$ approaches the value 1, if it be assumed that 600 revolutions of the bit have been made during the delivery of 1 in. of core; then $W = 5 \times 600$ or 3,000, which is indicative of the number of major vibrations of the bit with respect to the axis of the core during its spiral advance of 1 in.

When the pitch p is left-handed, $F(p)$ may be considered as varying from 0 to -1; when the pitch is right-handed $F(p)$ varies from 0 to $+1$. As p becomes small, in either case, the value of N increases and W increases approaching the case where many fine threads of low pitch are produced; W increases greatly, which is to say that a cylindrical core is formed when there is a large number of exceedingly small wave motions of the bit to and fro. Considering an instance when N remains constant and the threads ultimately coalesce while "p" decreases in value, then the value of W decreases. The ultimate end of this process is the production of a smooth core with slight wave motion of the bit.

Inspection of this equation shows that as R increases, W must increase. This expresses the violence of vibration when harmonic motion of the resonant type is set up during a high speed of revolution.

This mathematical statement is merely an attempt to express some of the relationships which appear, by speculating on the nature of the phenomenon. It is doubtful whether it is possible to determine rigidly the value of $F(p)$ in any instance or to tell why p should be left-handed or right-handed or to devise any means of telling why N is 5 in one case or 9 in another. The strength of the rods, the number and character of the carbon, the way they are set with respect to each other, the water pressure in the hole as determined by the force of the pump, the clearance of the bit, etc., the amount and character of the deformation in the metal of the bit at any particular time, the kind of drilling machine, and the manner of its set up, the depth drilled, the nature of the rock, the presence of soft horizons above in the hole which may affect the vibration of the rods, the speed of rotation and the pressure on the rods—the factors which influence these values are numerous and therefore difficult to analyze into their true proportions.

Practical Considerations

Dr. Crane's practical application of the results of his research is discouraging in these days of keen competition for drilling contracts. I refer to the suggestion that it is possible to reduce "the vibratory action of the drilling mechanism by reducing the speed of rotation of the rods." An old drillman in commenting on this says that he can break up the vibration by increasing the speed of rotation. This suggestion might better be stated thus: The violence of vibration can be broken up by varying the speed of rotation.

This destroys one of the constant conditions essential to harmonic motion. The greasing of the rods dampens the wave and sets up interference by releasing friction at antinodes of the waves, thus destroying another constant. This may be inferred by examining the line of greased rods when pulled from the hole and by observing that the grease is worn clean at definite intervals.

In making this comment on Dr. Crane's conclusion, I would not be understood as casting doubt on the utility of this type of research. An analysis of all the conditions which govern the advance of a diamond bit might enable operators to control the direction of diamond-drill holes. At present the hole usually takes its own direction.

Some practical considerations have occurred to me while dealing with the subject. They are no doubt commonplace to many old drillmen, but seem worth recording: When drilling deep holes in homogeneous formations, it will reduce the carbon wear and increase the footage to use stiff new rods and to use a blank bit which has the smallest possible excess in diameter over the size of the rods. The use of eight stones in a bit rather than four or six will reduce the possibility of one stone carrying the burden of the work. The bit should be reset frequently so that deformation of the weakened steel in long-used bits will be avoided; thus the gage of the hole may be kept more accurately. These precautions will set up conditions adverse to the development of resonant wave motion to and fro in a bit and thus tend to keep it working straight ahead, which is the true business of a diamond bit.