The Diastrophic Theory*

A Contribution to the Study of the Mechanics of Oil and Gas Accumulation in Commercial Deposits

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THE writer has devoted a number of years to practical operations and to the study of geology in the oil fields. In consequence, he has been brought to investigate the theories advanced to account for the accumulation of oil and gas in commercial deposits. It is the result of these investigations and his personal conclusions that he wishes to sum up in this paper.

The writer is an advocate of the organic origin of petroleum found in pools. He has been led to believe that the present theories of oil and gas accumulations are incomplete and, in certain respects, incorrect, although they may embody certain elements of truth; that the forces that are called upon to explain the movement are only secondary forces in the process, and insufficient, by themselves, to cause this movement; and that the phenomenon of accumulation is of much larger order than heretofore admitted and bears an intimate relation with the general as well as with the local deformations of the crust and is a direct consequence and a mechanical effect of these deformations to which the term "diastrophic" has been applied. As a complement to this theory, the writer offers a new interpretation of the "rock pressure" and of the mechanism of the "sealing up" of this pressure in oil and gas pools.

The Anticlinal Theory

The theory most generally accepted to account for the accumulation of hydrocarbons in commercial deposits is the anticlinal or structural theory. This theory, the principles of which have been laid down by I. C. White, Orton, Winchell and others, and which has since been modified and perfected, is too well known to need a detailed statement. A clear interpretation of it may be found, in the paper of W. T. Griswold, in *Bulletin No.* 318 *of the United States Geological Survey*, and the reader is

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referred to it. In this theory, the *force* which is supposed to have caused the motion is the gravity of the hydrocarbons; and the principal *factors* which have intervened in the process are the structure and the general stratigraphic conditions of the rocks, their texture and porosity, and their water content. The oil and the gas are supposed to enter the porous rock that is to act as a reservoir, by some indefinite process. Any further movement toward accumulation is only considered as possible if a dip exists in this rock sufficient to overcome the friction, and practically impervious areas of the rock will be more or less perfect barriers against the movement. Then, if this rock is completely saturated with water, or if the hydrocarbons have entered it below the line of complete saturation, the oil and the gas will gradually move up the slope by the effect of buoyancy; the gas, with its lower specific gravity, occupying the higher places. Should the rock be dry, or if the hydrocarbons have entered the rock above the line of saturation, the oil will flow down, as long as gravity is sufficient to overcome the resistance to motion, and the gas will diffuse with the air or water vapor contained in the pores of the rock.

From this statement it will appear that the following assumptions are an absolute requisite for the anticlinal theory:

First, the structural deformations (dips, anticlines and synclines, domes, terraces, etc.) must be supposed to have existed previous to the introduction of the hydrocarbons in the porous strata; in other words, it must be assumed that structural deformation has preceded the movement toward accumulation. Indeed, in this theory, the preëxistence of structural deformation is the very basis of the action of gravity and, at the same time, the theory implies that the forces which have caused the deformations have had no bearing on the movement of the hydrocarbons.

Second, gravity or buoyancy is to be considered the sole agency through which accumulation has been brought about and, as such, is supposed to be adequate to explain accumulation under any condition of dip.

To which the following considerations may be added: The movement toward accumulation would have to take place in the porous rocks when they are already solidified and partially cemented. There would be no connection between the causes which have led: To the introduction of the oil in the porous strata; to the movement of the fluids in these same strata; and to the "rock pressure" itself. Further, this theory does not provide for any satisfactory explanation as to the mechanism of the "sealing up" of the pressure in the pools.

The first assumption is begging the question. To the best knowledge of the writer, no attempt has been made by the authors of the theory even to discuss the point or to prove the accuracy of the inference. It seems as if, from the start, it was admitted as self-evident that the gravity of the fluids was the only possible force entering into action. The writer will try to show later on why, in his opinion, this assumption falls short of truth and how its admittance may be explained by the fact that the problem has not been attacked from its true angle. On this first point, to say the least, the anticlinal theory is not established on proven ground.

The second assumption may be seriously contested. The force of motion due to buoyancy is a function of the sine of the dip. It would be maximum for a vertical stratum and null for a horizontal one. Many anticlines in the Eastern fields of the United States have a dip so low that a motion caused by buoyancy alone could hardly be understood. Dr. Ashburner has found a maximum dip in the Bradford region of 69 ft. per mile, or less than 1 ft. for 76 ft., while Carll has shown that the dip of the oil sands in the Venango belt, and the southern end of the Butler belt, rarely exceeds 34 ft. per mile (Sir Boverton Redwood), or less than 1 ft. for 155 ft. In West Virginia, the maximum dip of many anticlines is less than 1 ft. for 50 ft., which corresponds to an angle of about 1° 8′ 45″. For this last dip, the force due to buoyancy, which is supposed to move the oil up the slope, would be reduced to 0.0066 of the weight of the oil, as pointed out by Malcolm J. Munn, of the U. S. Geological Survey. A volume of 1 c.c. of oil would thus be submitted to a moving force of a few milligrams. The oil could be set in motion only if this force were greater than the resistance due to static friction, viscosity and surface tension. It is not possible, with the data now at hand, to submit the question to a complete mathematical treatment. As Van Hise points out,[1] "the pore openings in sandstones are for the most part capillary", and the flow of oil through the rock would have to obey the laws of flow through capillary tubes, which are not yet satisfactorily expressed. Further, the pore openings would be extremely irregular in shape and dimensions. But it is possible to reduce the problem to a simpler form. If, barring viscosity and surface tension, we would only consider the resistance due to static friction, we would obtain an inferior limit to the resistance. And if it were possible to show that the force of motion due to buoyancy is insufficient to overcome such a frictional resistance, in the case under consideration, it would be proof that the anticlinal theory can not be accepted, at least in its present form, and that other forces besides buoyancy are to be considered in order to explain the motion.

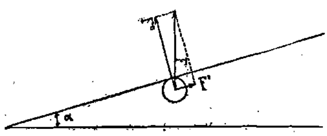

Fig. 1.

Let us imagine a globule of oil appressed against the roof of the sandstone stratum by the effect of buoyancy (Fig. 1). Let F be the force of buoyancy. This force may be decomposed into two components: F' parallel to the dip, which would cause the globule to slide along the roof, and F'' normal to the roof, which would press the drop of oil against it.

[1] A Treatise on Metamorphism, *Monograph* 47, *U. S. Geological Survey*, p. 138 (1904).

The effect of this pressure is to create a resistance to the sliding, which is proportional to the pressure and directed down dip. This proportion, which remains constant when the nature of the surface remains the same, is the friction coefficient. Let it be c. The movement will become possible only if $c < \frac{F'}{F''}$ or $c <$ tang α, α being the angle of the dip. If the dip is 1 ft. to 50 ft., the tangent is 0.02 and the condition reads $c < 0.02$.

There are no data available for the friction coefficient of oil and sandstone under the conditions stated. But one may get an idea of the order of magnitude of this coefficient by a simple experiment. Let us take a slab of some oil-bearing sandstone, some Berea grit, for instance. The lower surface of this slab must be planed, but not ground, so that the grains of sand remain entire. Let us immerse the slab in some salt water of proper density, in a horizontal position, and loosen a drop of oil from a syringe in the water, under the slab. The drop will rise to the bottom of it, and here it will remain if the slab is perfectly horizontal. Let us then incline the slab progressively and note the smallest angle of dip at which the drop will be set in motion. The tangent of this angle will be equal to the coefficient of static friction.

The writer has made this experiment repeatedly and has never succeeded in getting the drop in motion for any such angle as 2°, which would tend to prove that the coefficient is superior to the maximum limit required.

It is further to be noted that the spherical form is the general form of oil drops in an emulsion, where the particles of oil are, in great majority, very small; it is also the form which, every other thing being equal, offers the least resistance to motion. Hence, if the motion is shown to be impossible under this form, it will be equally impossible under any other form, and the whole theory falls through.

The change from a spherical form to an irregular one, by the flattening of the drops when compressed against the walls or when passing through irregular and narrow channels, the indentations, the penetration of the oil between the grains, the effect of viscosity, the capillary action—especially if gases be held in the emulsion—would be as many causes furthering an increased resistance to motion.

Now, the fact that the movement toward accumulation is not possible under the sole influence of gravity, with the low dips so characteristic of many oil regions, does not mean that gravity has had no influence in the process. It simply means that this force alone would be inadequate to explain the motion and that some other force or forces must have entered into play. But though gravity of hydrocarbons may not be a primary agent of their accumulation, it is a force which must be taken into account in any general theory of the process.

The Hydraulic Theory

In opposition to the anticlinal theory of oil and gas accumulation through gravity, Malcolm J. Munn has propounded[2] another theory in which the moving force would be the hydraulic (not hydrostatic) pressure and capillarity of underground waters. This is termed *the hydraulic theory.*

"The fundamental idea of the hydraulic theory," writes Mr. Munn, "is that moving water under either hydraulic or capillary pressure has been the direct agent of accumulation of oil and gas pools. To this idea may be added another of equal value—the pools of oil and gas are held in place by water under hydraulic and capillary pressure which effectively seals up all the pores of the surrounding rock and prevents the dissipation of pressure by diffusion." This theory is very interesting and, as will be seen later on, the writer agrees with Mr. Munn on two points, viz., that water under hydraulic pressure has really been the primary agent of motion, and that the "sealing up" of the pools is a phenomenon of surface tension. But, as far as the writer can see, Mr. Munn has reduced the hydraulic pressure to that of underground waters circulating in the same way as they do now, and his statement relating to "hydraulic and capillary pressure" is rather undetermined.

"Capillary pressure" is a somewhat misleading term. If by this is meant the general action of forces due to surface tension, it is well to note that surface tension may create a resistance against the flow as well as a tendency toward it, as Mr. Munn himself seems to acknowledge when he comes to the "sealing up" of the pools. If it simply means the process of infiltration, the creeping of a liquid through capillary channels, this process has its limitations and would seem to be a process of dissemination rather than of concentration. On the other hand, hydraulic pressure of underground waters may be inadequate. Hydraulic pressure is a function of the square of velocity, and the velocity of underground waters is known to be extremely small. "The motion of the ground water as a whole," writes C. S. Slichter,[3] "is somewhat like the slow motion of very viscous sirup or the slowly creeping ice of a glacier." It has been shown, for instance, that the ground waters of the Arkansas River flow in gravels at a rate not greater than 3 to 5 m. a day. This would mean a velocity between 0.00348 and 0.0058 cm. per second, or less than from 13 to 21 cm. per hour. It is possible to show that, should the static coefficient of friction between oil and sandstone be greater than 0.02, as heretofore admitted, a velocity of 0.006 cm.-sec. would not overcome the frictional resistance of oil in an inclosed pipe, on a horizontal

[2] *Economic Geology*, vol. 4, No. 6, p. 523 (September–October, 1909).

[3] The Motions of Underground Waters. *Water Supply Paper No.* 67, *U. S. Geological Survey*, p. 35.

plane, barring the additional resistances due to viscosity, surface tension, deformation, etc., which would interfere in this case. Though the analogy may not be entirely correct, it has a tendency to show that the influence of hydraulic pressure of underground waters is here doubtful and at least remote in importance. There will be always a great difference between the transportation of a material in the state of solution, which may be followed by subsequent re-deposition, and the transportation of insoluble solid material, as oil in water. Further, the theory is open to the same general line of objections as the anticlinal theory, and more so, as structural deformation, which is so intimately connected with the phenomenon of accumulation, becomes here entirely subordinate and incidental.

The Diastrophic Theory

The fundamental weakness of the theories which we have reviewed may perhaps be traced to the hesitation of the authors of these theories to choose deliberately between the different conceptions of the origin of oil itself. This origin once ascertained, it is evident that the surest way to determine how oil and gas may have accumulated in certain places, would be to try to follow the possible movements of the oil from the time of its first appearance in the strata, down to the pools where we find oil today. In order to be rational, a history ought to be complete; and we have no more right to limit the history of petroleum to the space of time during which the strata, in which we find it now, may have existed in the same present shape and condition, than we would have the right to reduce the story of a man to the last years of his life. It is further obvious that the history of petroleum will have to be entirely different, dependent upon its origin, either from emanations coming from the depths, or from organic decomposition in the strata themselves. In the writer's opinion, many reasons favor the theory of organic origin for the petroleum found in commercial deposits, though this does not mean that petroleum of a different origin does not exist elsewhere. Hence, this is a point on which we have first to agree, or else agree to disagree. Should the organic origin of the petroleum that is found in pools be granted, the following interpretation is offered for the mechanics of its accumulation.

Oil developed by the process of decomposition of organic matter—whether vegetal, animal or both—would have first to exist in the sediments which contain the parent matter, in the state of dissemination. As Orton remarks, "disseminated petroleum is well nigh universal, but accumulations are rare."

In order that such an accumulation of disseminated particles may take place, three elements are necessary: An adequate source of supply; a reservoir to hold the oil and accompanying gas under pressure, and a process of concentrating the disseminated material and conveying it to the reservoir. The source of supply will have to be ascertained in every individual case. It is supposed here to exist, for the sake of argument. The reservoir is easy to imagine, inasmuch as we are able to corroborate our theoretical views by actual knowledge. A porous stratum overlaid by an impervious one, may act as a reservoir. This is the general case. Or the reservoir may be constituted by a porous stratum highly inclined and cut off abruptly below ground by a fault, which thus seals the oil and gas and prevents their escape. This kind is found in some Californian fields and elsewhere. Or the reservoir may be constituted by joint cracks in a shale, as is the case in the Florence oil field, Colorado,[4] etc.

The interpretation of the process of concentration and eventual migration, *i.e.*, of accumulation, is more complicated. As a natural process, it must obey physical laws, and especially the laws which govern the motion of fluids and gases; but the *forces* which may cause the motion (gravity in its different forms, heat, surface tension), the *agents* through which these forces accomplish certain results (water, oil and gas in varying physical or chemical states), and the *factors* that intervene in the process (structure and texture of the rocks, porosity, stratigraphic conditions, water and gaseous contents, viscosity, capillarity, depth and time) may have or have had a widely varying range of influence, according to past and present conditions. These elements would have to be seriated, according to their probable rank of importance, and their relative degree of influence determined, before a tentative conclusion could be reached. It thus becomes evident that if some broad general principle may be laid down, a great number of variations are to be expected for each individual case.

A few general observations may help us from the start. According to the organic theory, which is accepted here, the ultimate source of the hydrocarbons is to be found in sedimentary organic deposits, and oil accumulations in commercial quantities (oil pools) are always associated with sedimentary strata. The immediate inference is that hydrocarbons must have been submitted, from the date of their origin, to the action of the forces that may have affected these same strata.

If we refer to a map of the known oil fields of the globe, we will notice, with Sir Boverton Redwood, that "whilst petroleum exists very generally distributed throughout the world, the principal deposits occur along well-defined lines, often associated with the principal mountain chains." This remark is important and deserves to be emphasized. It means that petroleum deposits are mainly associated with the lines of lesser resistance of the globe, with the general direction of geosynclines and consequently with the areas of general orographic movement and deformation. The distribution of the Eastern oil fields of the United States and Canada along the Paleozoic trough, or geosyncline, of the

[4] C. W. Washburne. *Bulletin No.* 381, *U. S. Geological Survey.*

Appalachian region, the location of the Western oil fields of the Pacific coast, from Alaska to California, followed by the Mexican oil fields, the deposits of the West Indies, of the northern coast of Venezuela, Columbia and a part of the Andes, along the general trend of a Mesozoic syncline; the oil fields of Galicia, Roumania, of the Caucasus, of Burma, of the Islands of Java, Sumatra, Borneo and New Zealand, following the path of another syncline, are extremely suggestive.

This first observation may be completed by a second. An oil field is always accompanied by a certain amount of local structural deformation, which sometimes is reduced to simple undulations, as is the case of the Appalachian region, or may reach a stage of high disturbance, with contorted strata, as is the case of the Galician oil fields. But local deformation has been observed everywhere. It becomes thus difficult to escape the impression that structural deformation, general as well as local, is more or less connected with the phenomenon of accumulation, and our inquiry is thus directed toward the possible action of the forces which have produced these deformations in the sediments from which hydrocarbons have proceeded and their possible action on the hydrocarbons themselves.

As stated before, oil would have first to exist in the stratum where organic decomposition takes place, in the shape of a finely disseminated matter. The sediments themselves would have to be deposited under water, in lagoons, marshes, deltas or at the bottom of the seas, in the form of mud or ooze. Such a mud would be composed of extremely fine mineral particles, intermingled with water in large amount. The particles of oil would take the form of spherical globules under the influence of surface tension, and, as these globules would be larger than the mineral particles of mud, they would be mechanically held in the mixture. Experiments conducted by Murray Stuart, Assistant Superintendent of the Geological Survey of India, and others, have clearly established this capacity of muds to hold oil in sediments by purely mechanical action.[5]

The preceding condition may be termed the *first phase* of the process. It is characterized by a layer of mud or ooze, holding mechanically, between its very fine mineral particles, disseminated drops of oil and gas bubbles, in a "matrix of water," as Murray Stuart expresses it.

When the conditions of sedimentation which allowed the deposition of the mud have changed, some other material may be deposited over this first layer; say some sand. Then, another change in sedimentary conditions will occur, and a new layer of material will cover the sand; suppose another layer of mud; and so on, successive layers of various sediments will be piled up in the sedimentary syncline.

Now, the progressive increase of weight due to this accumulation of

[5] *Records of the Geological Survey of India*, vol. 40, Pt. 4, pp. 320–333 (November, 1910), and *Economic Geology*, vol. 7, No. 1, p. 91 (January, 1912).

successive layers will cause a progressive compression to take place. The effect of compression on a mass of practically incompressible mineral particles imbedded in water is to draw these particles closer together, to reduce the space available between them, and to squeeze out more or less of the liquid contents. The limit of compression is reached when the particles come in contact. For this reason, the result would be somewhat different, according to the size of the component particles of the layers. Mud or ooze particles are exceedingly small. When, in the syncline, the lower layer of mud would be compressed, the resulting texture would be close, and the tendency would be for the fluids to be squeezed out to a great extent; whereas the grains of a layer of sand are much larger than the particles of clay, and such a layer may become incompressible when it still contains a great percentage of holes. It may thus act as a reservoir for liquids even under considerable pressure. The overlying sand stratum would then remain porous to a large extent, and the liquids, escaping from the underlying mud, would rise and become confined in it. This may be termed the *second phase* of the process, and is characterized by the progressive transfer of a large part of the oil and gas from the clayey layer in which they have originated to the overlying porous stratum in which they still remain distributed in a finely disseminated state. At this stage, the porous rock may be supposed to be saturated with an emulsion of oil and gas in water.

Finally, in the course of time, sedimentation is stopped in the syncline of deposition, and orogenic movement begins. Whatever may be the cause of this movement, it is a tendency toward a new adjustment which evinces itself by a lateral thrust. In the simpler form, one rim of the syncline remains immovable, and acts as a resistance, and the other rim is brought nearer to the first one by a movement tangential to the crust, which squeezes the syncline as between the jaws of a vise. The strata are bent and lifted above the level of the waters.

It is possible to get an idea of the order of magnitude of the thrust and to compare it with the forces due to buoyancy and hydraulic pressure invoked in the preceding theories, and which we have found to be insufficient to explain the migration of the oil. For this, we have to consider that this new force exceeds the resistance to crushing offered by the most resistant sedimentary rocks. This crushing strength becomes thus an inferior limit to the force. Limestone, for instance, may be crushed under a pressure of between 400 to 1,200 kg. per square centimeter; so the thrust is to be measured at least in hundred kilograms to the square centimeter. We have already seen that the force of buoyancy, by which a cubic centimeter of oil is supposed to be lifted along a dip in the anticlinal theory, is to be measured in fractions of a gram (in milligrams for a dip of 1 ft. for 50 ft.), and hydraulic pressure due to underground waters, with the velocity admitted, would be still less important. The magnitude of the force we are considering now—the tangential thrust—is then at least one million times greater per unit surface than the two other forces previously considered. Further, this force has left its imprint in all sedimentary strata, not only by the flexure of the strata or their relative displacement, but frequently by dynamo-metamorphic actions which it has brought about. These actions have taken place between the time the strata were lying at the bottom of the waters and the time they have acquired their present situation. If then, any oil was ever existing at the

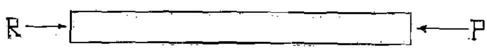

FIG. 2.

time of the deposition of the strata and has remained in some stratum since, it must equally have been subjected to the action of the thrust. The *third phase* of the process begins with this action of the thrust. But this needs a more complete analysis of facts.

When a square prism of a solid material, such as a piece of wood or an iron bar (Fig. 2), disposed horizontally on a support in order to avoid the action of gravity, and propped against a resistance R at one end, is com-

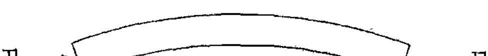

FIG. 3.

pressed at the other end by a force P, in the direction of its axis, the compression is instantaneously transmitted to the resistance, from end to end. Then, if the pressure is sufficiently increased, the prism will bend (Fig. 3). This flexion will extend the fibers on the convex side and contract them on the concave one, and there will be an intermediate layer which will be neither contracted nor extended by the flexion. This

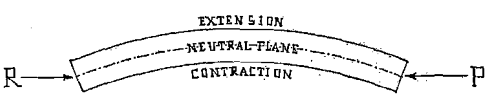

FIG. 4.

is the neutral plane (Fig. 4). Superimposed to this first effect, there will be a general contraction along the axis, which will affect the whole prism.

If, instead of a prism of solid material, we operate on a prism made of some homogeneous plastic material, like moist clay, the result would not be exactly the same. The compression at one end would not be immediately transmitted at the other end, but only progressively, in proportion as the inertia of the successive sections of the prism and the friction against the supporting stand would be overcome, the one after the other. And deformation would begin at the end where the thrust *P* is applied, even before any compression would become noticeable at the other end, if the prism were long enough.

Let us now imagine a prism composed of a series of parallel, superposed, horizontal and homogeneous layers, individually uniform in thickness, but variable in composition and resistance, such as clayey, sandy and calcareous layers would be. Suppose such a prism submitted to a uniformly distributed load, representing the load of superincumbent strata; the friction against the stand reduced by the interposition of a soft base, and proper precautions taken to avoid lateral deformation. And let us subject this prism to the same process of compression. Here again the compression would be transmitted progressively from the point of applied pressure to the point of applied resistance, and deformation would begin at the extremity nearer to the thrust. This deformation may vary, according to the relative thickness and disposition of the "competent" and "incompetent" strata, as they have been termed, but would generally take the form of a local bend, some sort of anticline, which may be overthrown in the direction of the resistance. If now

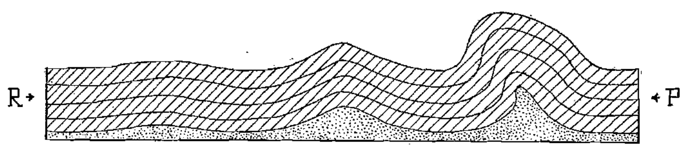

FIG. 5.

the pressure should be continued, waves would rise in succession, from right to left, decreasing in height, the farther they reach toward the resistance, and the flexed prism would finally take the general appearance of Fig. 5. The mechanical result would be: (1) A general compression of the prism, which would decrease from *P* to *R*, where it might disappear, and (2) deformations by bending, with appressed folds toward *P* and lower anticlines toward *R*; the folds being generally overthrown in the direction of the resistance *R*.

Now, we have already seen that when a material is compressible, compression will tend to draw nearer to each other the solid particles of which the material is composed. Compression would thus tend to a reduction of volume and to a reduction of porosity, or capacity for liquids. The first mechanical effect of our experiment, then, tends to reduce the capacity for liquids of the material at a decreasing rate from *P* to *R*, from the point of applied pressure to the point of applied resistance.

To this would be superimposed the mechanical effect due to flexure. Anticlines would be extended on their convex side and synclines compressed on their concave side. If, then, the thickness of the prism is sufficient, and if we consider only its upper portion, above the neutral plane, the general effect would be as follows: A general decrease of compression and a general increase of capacity for liquids from P to R, superimposed on a wavy succession of local increases and decreases of capacity. This would create a succession of zones of increasing capacity from right to left (from P to R), individually elongated in a transverse direction to the prism, or in a parallel direction to the folds. If then the porous strata were saturated with a liquid, the tendency would be for the liquid to move from the more compressed parts to the less compressed or decompressed ones. This movement would take place along the lines of lesser resistance; viz., (*a*) from the clayey layers to the sand strata, which would complete the concentration of the oil emulsion, already begun by the effect of vertical compression, into the sandy layers, and (*b*) along the sand strata themselves. Pools would be constituted parallel to the flexures, which would become more important the nearer they approached the resistance, or increasing from right to left.

Further, compression and consequent migration of the emulsion through the sand would have a tendency to allow oil drops and gas bubbles to coalesce. Temperature may play a part in the phenomenon, as pressure would generate heat. This heat may be negligible in the zone of reduced compression, but may be important in the highly compressed one. Rocks may afford sometimes a certain amount of heat without noticeable changes; but organic liquids would be more or less modified. A slight increase of temperature would lower the viscosity of the oil and facilitate its migration. A sufficient rise may partially decompose it, and complex reactions may occur if this decomposition should take place under pressure, in the presence of water vapor. This side of the question will have to be investigated more completely, should the general theory be admitted. For there could be found possibly a partial origin of the different grades of oil, and the source of a large part of the gas which accompanies oil in the pools today. The complexity of the products would still be increased by the filtration of the oil through certain rocks, which an excessive compression may allow, or which capillarity may induce in other circumstances.

At any rate, gas and oil concentration in the zones of decompression or of reduced compression would result; and water, oil, and gas may finally settle in the reservoirs according to density.

On the other hand, we have seen that the anticlines would be extended along their crests and the synclines contracted along their bottoms, if we consider only the part of the prism above its neutral plane. The liquid would thus be squeezed out from the synclines and would have a natural tendency to collect, by the effect of compression, in the higher and more open parts of the anticlines. Later, if, for some reason, water were reduced in amount, the oil would follow the level of the receding waters and sink toward the bottom of the synclines, as long as porosity would permit.

It might occur, with a sufficient increase of the lateral thrust, that the material subjected to compression would break instead of bend, and that overthrusts and faults would result. These deformations would naturally take place in the more compressed region, on the side of the thrust. This would open a way of escape to the gas and to the liquids, and the affected parts of the oil-bearing strata might be deprived of their contents, by outflow or evaporation. The oil and gas would be lost and these parts of the layers would become dry.

As far as we have gone, we have considered theoretical views and results of laboratory experiments only. The material which we have been handling was simple, the individual layers homogeneous, of constant thickness and horizontally disposed; the forces were acting in the vertical plane of symmetry of the prism, etc. And from a starting point fraught with geometric simplicity we have reached simple and geometric results. The merit of this way of proceeding is that it has allowed us to understand more clearly than could be done otherwise, the trend of events when the elements of the problem are reduced to their simpler lines.

But in Nature, things are much more complicated. Let us consider, instead of a prism, a syncline of deposition and note the new set of conditions which may affect the result. Between the geometric dispositions of our previous scheme and the dispositions encountered in the field, we will remark at once the following differences:

The material will not be homogeneous, but varied to the extreme. Not only will the strata be different from one another in composition, texture, resistance, flexibility, etc., creating a lack of homogeneity in the vertical direction, but similar differences will be found in individual strata, so that the lack of homogeneity will become almost general.

The materials will not be geometrically disposed. The outlines of the compressed area, in horizontal projection, will be irregular, and its thickness at great variance from point to point. The layers will be incurved, presenting original bends of deposition. Their own thickness will be irregular, and the so-called "planes of stratification" will not be planes at all, but complicated surfaces.

If we consider one particular stratum, the pressure due to overlying formations will not be the same everywhere.

The thrust will be irregular, and to simple compression and flexion will be superimposed a torsional movement. Consecutive thrusts, varied in direction and importance may affect the same region. Further, an orogenic movement does not result simply in a series of more or less parallel folds, elongated in one direction; it is complicated by transverse or orthogonal undulations, which create successive elevated and depressed areas along the general strike of the folds; the anticlines have a tendency to be transformed into elongated domes, the synclines into elongated basins.

Finally, breaks of greater or lesser magnitude frequently occur in the folded masses, and faults and overthrusts take place.

For these reasons, the resulting structure of a syncline subjected to orogenic movement becomes sometimes very intricate. Further, the superposition to the simpler effect of lateral compression of a series of incidental effects, derived from irregular forces which enter into play, would put the problem out of reach of mathematical treatment.

But there remains a way open to us. We may consider such a deformed syncline in nature, and try to ascertain how much the facts collected in the field may agree with the general lines of our theoretical views.

A good example of a folded chain may be found in the mountain system of the Appalachian province, which extends from New York to Alabama with a general northeast-southwest trend, and in the immediate neighborhood of which some of the most productive oil fields of the United States are situated. The thrust is supposed here to have taken place from the southeast. The whole Paleozoic series of strata to the floor of the crystalline Archean rocks—in some parts 40,000 ft. thick—have been involved in the system of flexure. The flexures are generally parallel to the main direction of the chain, and tend to be arranged *en échelons* in overlapping series. They are mostly unsymmetrical, *i.e.*, they bear a "rear and front structure," the steeper side generally facing northwest, away from the Atlantic Ocean. Bailey Willis, in his *Mechanics of the Appalachian Structure,* recognizes four districts in the Appalachian belt. The eastern portion of the system is a district of "close folding," extending nearly its entire length and terminated at the south by a district of "folding with cleavage." The western part of the belt, on the north, through central Pennsylvania and the Virginias, is a district of "open folding." South of it, and always on the western side of the belt, comes a district of "folding and faulting," which passes through eastern Kentucky and Tennessee to Alabama.

The district of "open folding" terminates, on the west, in large undulations of low dip and merges finally into the monoclinal or gently undulating structure of northwestern Pennsylvania and eastern Ohio.

Beyond the southern region of "folding and faulting," proceeding westward, comes the high plateau or tableland of Kentucky and Tennessee.

As a whole, and barring irregularities of detail, we find here the characteristics which have been outlined in our theoretical statement: Successive parallel folds, more closely appressed on the east (the side of the thrust) and decreasing in importance the farther we come west (toward the resistance), with a general tendency for an overthrow of the folds in the direction of the resistance.

All the oil and gas fields are located along the western side of this belt, on its outer margin; *i.e.*, on the side that is farther from the point of application of the thrust. From Pennsylvania down to Alabama, their main direction closely follows the direction of the chain, and individual pools are frequently disposed in rudely parallel rows, with their major axis parallel to the folds. This parallelism between the positions of the oil and gas areas and the trend of the mountains has long ago been pointed out, especially for western Pennsylvania.

Another remark is that the oil belt is especially developed in front of the region of "open folding," to the north, but rapidly decreases in importance as soon as it reaches the front of the region of "folding and faulting," to the south. The effect of faulting would be to relieve the strains and, in so doing, to reduce the amount of deformation farther west, as well as to open a way of escape to the fluids, if any. This double effect would reduce the tendency toward accumulation.

The Pennsylvanian oil belt offers a further interesting feature. When entering the State from the south, the mountain belt is at first bent eastward in its trend, and it takes again a northern course after crossing the Susquehanna. Fig. 6 represents this curve, which has the form of the letter *S*. Now, incurvations of this kind are frequently encountered in mountain chains, and they have been interpreted sometimes as the result of the resistance against orogenic movement due to an ancient mass of consolidated rocks (*Massif d'ancienne consolidation*) in the region *M*, acting as a pier which would deflect the direction of the thrust. The mechanical effect of such a deflection would be an increased pressure in the concave part of the curve, toward *A*, and a decompression in the region *B*, where the curve becomes convex. The fact that the principal oil areas of Pennsylvania and southwestern New York—which are among the most productive in existence—are located precisely in this zone of decompression and do not extend farther east in the compressed zone, is interesting.

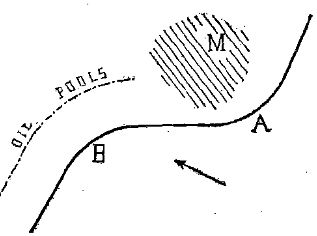

FIG. 6.

The same relations between orogenic deformations and oil-producing areas may be observed in other fields, as, for instance, in the oil fields of central Europe. The chain of the Alps, followed by the Carpathian Mountains, the Transylvanian Alps and the Balkans, are interpreted today as a system of folded chains. The belt develops from southern France to Galicia, Bukowina, and northern Roumania in the form of an arc, with its convexity directed northward. Its eastern extremity presents the well-known sigmoidal inflexion formed by the Transylvanian Mountains and the Balkans. The thrust has been directed from the inside of the curve toward the outside. Everywhere, the oil fields are located on the exterior slopes of the belt; *i.e.*, on the side that is farther from the point of application of the thrust, and the pools are distributed in rows parallel to the trend of the folds, frequently with their major axis in the same direction.

In these districts the deformations are no more the gentle anticlines and synclines or the terraces of the Appalachian region; the strata are highly disturbed, contorted and even faulted. The thrust in the Alpine belt has been much more powerful than in the Appalachian region, and in certain places overthrusts of considerable magnitude have taken place. In fact, the Alps proper and the Carpathians seem to have been submitted to folding and deformation at least at two different periods: First immediately after Oligocene times, and second during the middle Miocene; and the present state of affairs is the result of the cumulative effect of both thrusts. It seems reasonable to admit that the region has passed through a first stage similar in some respects to the one presented by the Appalachian belt, and during which the greater part of the accumulation may have been effected, before reaching the further stage of greater disturbance, in which a part only of the accumulated hydrocarbons seems to have been preserved, in consequence of special stratigraphic conditions.

Similar relations may be observed in many other fields.

The preceding remarks have led the writer to believe that the facts observed in the field agree with the theoretical views previously expressed, and the hypothesis which he proposes for oil and gas accumulation may be summarized as follows:

First Stage.—The oil proceeding from organic remains, perhaps still in process of decomposition at the very origin of the movement, is at first distributed in the water-laden sediments of the geosyncline of deposition in the state of disseminated particles.

Second Stage.—The increasing compression, due to the continuous accumulation of superimposed strata, expels an increasing amount of the water of deposition with its contents of hydrocarbons, from the original layers, which, at the same time, are the most easily affected by the compression (argillaceous or limy sediments), to some other layers less affected by it (especially sands and gravels). This displacement may take an upward or a downward trend, the only condition being that the fluids must move along the line of lesser resistance, from a more compressed to a less compressed zone. This movement may take place between two entirely different strata, or between two layers of the same group of deposits, provided the layer acting as a temporary reservoir is less compressible or more porous than the former one. (This latter condition obtains in the dolomitic layers of the Trenton rock.)

Third Stage.—As soon as orogenic movement begins, a more or less horizontal compression, due to the thrust, takes place and becomes added to the vertical pressure due to superincumbent weight. The result of the intervention of this new force is to create: first, a general increase of compression from the point of applied resistance to the point of applied lateral pressure; second, successive and parallel zones alternately compressed and decompressed, whose strike is normal to the direction of the thrust. The waters which saturate the strata are submitted to the effect of this unequal pressure and move from the highly compressed regions to the lesser compressed ones, carrying the hydrocarbons with them in their course, finally collecting in pools parallel to the folds. The movement would have to take place along the lines of lesser resistance, *i.e.*, toward and along the more porous layers of the formation (sandy layers, etc.). Pressure would reduce the viscosity of the oil, favor the coalescence of the globules and perhaps induce some chemical changes of the hydrocarbons. The more probable places of accumulation would be the crest of anticlines, the summit of domes, the rims of terraces, or, in the main, the places where a change occurs in the dip or along the strike of the strata, in the form of convex edges or arches; for the reason that at these places the local reduction of compression, buoyancy, and resistance to motion due to a change in the direction of flow, would act together and accumulate their effect.

When the fluids reach the zones of lesser compression, if the physical condition of the reservoir in which they collect is such as to hold the hydrocarbons and prevent their escape, an equilibrium is established, and the final pressure in the pools must be equal to the original pressure less the losses of head encountered on the way.

Further, a progressive settlement would take place in the reservoir, according to gravity; water would congregate at the lower places, oil would have a tendency to collect at its surface, and gas—either brought with the water or dissolved in the oil and further released by decompression, or simply produced from the oil itself—would reach the higher places.

Considered as a whole, the process would be a consequence of the mechanical principle of least action. In this process, the agent of transportation of the hydrocarbons would be water; the moving force would be hydraulic pressure created by vertical and lateral compression; and the extent of the movement would be variable in the extreme according to local conditions of the strata. But compression, especially compression due to the lateral thrust, whose action would be irregular and continuous and would have to be extended over a long period of time, would not act as the permanent head of water which nowadays is the ultimate source of the velocity and of the hydraulic power of circulating underground waters. Frictional resistance may reduce and even stop the motion of underground water once for all in a given direction; a thrust would act by a succession of jerks and repeat the effort again and again. There would be periods of activity, during which the compressive force would exceed the resistance of the rocks and deformations would ensue, followed by periods of rest, brought by the momentary relaxation of stresses due to deformation itself and during which the compressive forces would accumulate; and the thrust would become the source of a periodically renewed energy. The consequent hydraulic pressure would follow a similar wavy movement, with periods of maxima, to which a maximum of velocity would correspond, and periods of minima or of rest, where frictional resistance might bring the movement to a stop. The action of the liquids would thus become similar to that of a water ram, with a maximum of efficiency periodically renewed.[6]

Fourth Stage.—A new stage will be reached by the gradual reduction of the water contents of the strata, producing consequent changes in the level of complete saturation and in the local disposition of the pools, by gravity.

Fifth Stage.—Sometimes, a new period of folding may take place, in which the thrust may have or may not have the same direction as the previous one. New zones of compression and decompression may be created, and the liquids may be put again in motion. The results may become thus very intricate, especially if the strata are deformed to a large extent.

All gradations must be expected to be found in the oil fields between these two extreme sets of conditions. The Appalachian belt may represent the first set, which stops at the fourth stage of our description. The fields of central Europe would represent the further and more complex stage.

The research for oil becomes thus a problem of tectonic effects as well as of stratigraphy.

Rock Pressure

The origin of "rock pressure" has been traced to one of the following causes: Hydrostatic pressure, weight of superincumbent strata, gradual accumulation of the inclosed gas, capillary diffusion.

The hypothesis of hydrostatic pressure is untenable as a general one. Hydrostatic pressure would agree, to some extent, with the pressure found in Ohio and Indiana, but could not account for the heavy pressures encountered in western Pennsylvania, as shown by Prof. J. P. Lesley and J. F. Carll, nor for the pressure of most of the deep West Virginia wells. Further, this theory is contradicted by the well-known fact that flow and pressure are found to decrease in any given well with the age of the well. A certain amount of constancy in the flow and in the pressure ought to be expected under artesian action, which is not the case.

The weight of overlying strata, under *present* conditions of the rocks would be mechanically inadequate.

[6] Dynamical action of the water ram type seems to have played an important part in certain geologic phenomena; the liquid being an aqueous or a magmatic solution.

The progressive accumulation of the gas may be a cause of pressure, and, according to David T. Day's experiments, capillary diffusion through fuller's earth bears a curious analogy with osmotic phenomena and the pressure due to this cause may be compared with osmotic pressure. But, if both theories may explain the origin of a certain pressure, they are not entirely satisfactory, in the writer's mind, for the following reasons: The progressive accumulation of the gas would rapidly be checked by the increasing pressure itself, and it has not been shown that such a limitation would not occur before reaching the high pressures encountered in some wells. On the other hand, the action of capillary diffusion seems to require certain physical conditions which are not met everywhere, and therefore it can not be admitted as a general cause. Further, none of the preceding theories explain the following facts: At least in the eastern fields of the United States, the rock pressure, in the main, increases with the depth of the "sand," and, at the same time, there seems to be a decrease of pressure with an increase of distance from the principal axis of the folding. The closed pressure in the Trenton limestone of Ohio and Indiana averages 200 to 300 lb. per square inch and only exceptionally reaches over 600 lb.; whereas the pressures in western Pennsylvania and in West Virginia, farther east, easily reach the double figure. In other words, it seems as if the pressure would increase, as a whole, in the same direction as the compression to which the rocks have been submitted at the time of their folding, both vertically and horizontally. A partial origin of the rock pressure, at least, would thus have to be traced to orogenic deformation. The two other forces—due to progressive gas increase and capillary diffusion—may have, and possibly have played a more or less important part in the final result, but this effect would have been produced later, and, in this respect, is to be considered as subordinate.

How Capillary Pressure Seals an Oil Pool

One of the most interesting problems involved in the study of oil and gas accumulation is the process by which gas or oil may accumulate in the pay streaks under heavy pressure, without this pressure being dissipated through neighboring rocks or through the sandstones. Imperviousness of the superincumbent strata and of the oil-bearing bed itself has been frequently advocated. But unaltered rocks of the type encountered in oil fields are never impervious. From 10 to 40 per cent. of their bulk is made of pore space, and the pore space of the inclosing beds of shales averages no less than 6 per cent., which means that every square foot of so-called impervious rocks contains an average of 8½ in. of holes (M. J. Munn).

In his "hydraulic theory," M. J. Munn has suggested[7] that "the

[7] The Anticlinal and Hydraulic Theories of Oil and Gas Accumulation, *Economic Geology*, vol. 4, No. 6, pp. 523 and 527.

pools of oil and gas are held in place by water under hydraulic and capillary pressure which effectively seals up the pores of the surrounding rock, and prevents the dissipation of pressure by diffusion." "Pressure in pools," he writes, "is maintained by the expansive force exerted by gas. . . . Such gas could not diffuse because of the saturated conditions of the surrounding rocks." But Mr. Munn does not go further than a general statement, and no detailed explanation of the process by which such a "sealing up" is rendered possible has yet been given, as far as the writer knows. The following is proposed as a tentative explanation.

Hydraulic pressure is here discarded, this problem being a problem of statics rather than of dynamics, and in which the velocity is naught.

There is a peculiar and interesting phenomenon which appears to have escaped the notice of those who have tried to explain the "sealing up" of a pool. It has been pointed out by Jamin, a French physicist, and is illustrated by the experiment of "Jamin's tubes." If a capillary tube is incompletely filled by water and the water distributed through the tube in such a way as to constitute a string of droplets, a pressure may be applied to one of the extremities of the tube which will not be transmitted to the other end. In other words, the string of droplets will act as a resistance. If there is a large number of drops in the tube, the difference of pressure at the ends arising in this way may amount to several atmospheres. The explanation follows: A drop of liquid, will be limited on both ends by a meniscus (Fig. 7). The superficial tension which results in this form is caused by the tension of glass and air, glass and liquid, and air and liquid. The two first sets of forces are parallel to the axis of the tube, and, being equal and directly opposed two by two at both ends of the drop, neutralize each other when conditions of equilibrium are formulated. The third set of forces, caused by the tension of air and liquid, is tangent to the meniscus all around the tube, at both ends, as shown in the figure, and makes with the axis of the tube an angle θ which is the "angle of contact." This angle will have a finite value if the liquid is oil or ground water (which is not pure water, but a salt solution, in this case fouled with traces of oil). The weight of the drop may be neglected here, as its action is insignificant with regard to that of surface tension. When the pressure is equal at both ends of the drop, the meniscuses are identical, and so are the angles of contact θ and θ'. But if the pressure P at one end is increased, both meniscuses will alter their curvature. The meniscus in front of P will decrease its angle θ, which will tend toward zero, whereas the meniscus opposed to P' will increase its angle θ', which will tend toward 90°. The result of this deformation is to increase the force $T \cos \theta$ directed against P, and to decrease the force $T \cos \theta'$ directed with it. The dif-

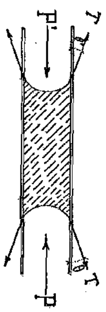

FIG. 7.

erence will be a resistance against motion expressed by $T(\cos\theta - \cos\theta')$, which will draw closer to the limit T as the pressure is increased.

The same conditions would obtain in shales or clays capping a gas pool. There is nothing like a plane of separation between the gas of the pool and the water that fills the pores of the superincumbent rock; but there is a more or less irregular intermediate zone in which the gas and the water are commingled. The pores of the shale, by their juxtaposition, would constitute the Jamin tubes of the experiment, and these would be filled by the mixture, which would take the form of bubbles of gas intermingled with droplets of water.

Van Hise remarks[8] that "the majority of the particles of most clays, shales and slates are much smaller than 0.0012 mm., and therefore the openings of the rocks are subcapillary." He defines subcapillary openings as those which are 0.0002 mm. and less in diameter. Starting from these data, it is possible to calculate, with a sufficient degree of approximation, the thickness of the shales or of the clay that would seal up a given pressure. The writer has found that a few feet would be amply sufficient to seal up a pressure of 1,200 lb. per square inch.

It may be conceived that the same process would apply for the sealing of gas and oil pools laterally, along the dip and strike of the porous layers themselves, wherever the sealing is not already produced by changes in the nature of the "sand" from a pervious to an impervious one, or by the presence of water. Pore openings of sandstones are, for the most part, capillary; and should water not be present in the sand, oil may replace it for the Jamin tube effect. Calculation shows that the marginal zone thus constituted may reach a width of a few hundred feet. Pressure would decrease in this zone from the inside to the outside of the pool, progressively, a feature which is readily observed in the field.

Discussion

Eugène Coste, Calgary, Alberta (communication to the Secretary*).—This new theory to account for the accumulation of commercial deposits of oil and gas, is deliberately and admittedly based on the hypothesis that the origin of these products is organic. Mr. Daly says (page 738), "Should the organic origin of the petroleum that is found in pools be granted, the following interpretation is offered for the mechanics of its accumulation." But suppose the origin thus accepted by definition be incorrect, then what becomes of the diastrophic theory, Mr. Daly's interpretation? As Mr. Daly remarks himself (same page), "It is obvious that the history of petroleum will have to be entirely different, dependent

[8] A Treatise on Metamorphism, *Monograph* 47, *U. S. Geological Survey*, p. 138 (1904).

* Received July 31, 1916.

upon its origin, either from emanations coming from the depths, or from organic decomposition in the strata themselves." Then why should one propound a theory, through which he is endeavoring to trace the history of petroleum, by starting with a definition of its origin? The origin should be the deduction, the forced conclusion of the theory, and not its starting point. Facts alone should be considered first, in any theory worth the name, until sufficient proofs have accumulated to permit of the deduction of a complete explanation for these facts. This would lead one to the origin through a real theory founded on facts, and not based on a preconceived idea perhaps true, but possibly fanciful. Mr. Daly's way can only lead on one road, namely the organic road, and, I repeat, it may be the wrong road.

In the case of the petroleum deposits, as I have endeavored to show in several papers on the subject, to which the reader may refer,[1] the facts clearly lead to the forced conclusion that their origin is not one of accumulations of hydrocarbons at first disseminated in the sedimentary strata but the reverse process of subsequent local infiltrations and impregnations of hydrocarbon emanations from the depths. This new theory, therefore, founded on an erroneous conception of origin cannot be a help in the solution of the petroleum problem, not any more than were the anticlinal theory or the hydraulic theory, both of which were also based on the same error, although Mr. Daly is inclined to think that the authors of these two theories did not accept the misconception boldly enough (page 738).

A careful reading of Mr. Daly's paper shows plainly the consequences of a wrong start, as it leads him to the following fallacies:

1. That oil and gas are (first phase of Mr. Daly's process) primary decomposed products of organic matter formed in the sediments shortly after their deposition at ordinary low temperatures, and held by them for a short period of time, until squeezed up into a porous rock deposited above just at the right time to receive them. This is a very different conception from the view held by other organists (geologists believing in the organic origin of petroleums) who hold, on the contrary, that only a very long time (aeons of ages) will cause the distillations of organic matter in the strata—this immensely long time finally accomplishing the same result as heat in ordinary distillation processes. But if Mr. Daly's view be correct, deposits of that kind should be frequent in nature, and yet no one has ever been able to observe them. As a matter of fact they do not and never did exist, as organic matter decomposes into entirely

[1] *Journal of the Canadian Mining Institute*, vol. 3, pp. 68–89 (1900), vol. 6, pp. 73–128 (1903) and vol. 12, pp. 273–302 (1909).

Trans., vol. 35, pp. 288–297 (1905) and vol. 48, pp. 504–517 (1914).

Transactions of the Institution of Mining and Metallurgy, vol. 21, pp. 91–192 (1911–1912).

different products which either escape immediately out of the forming sediments, or finally transform into carbonaceous matter or coal without any other hydrocarbon but marsh gas being produced.

2. That porous rocks shortly after their formation (second phase of Mr. Daly's process) may be supposed to be saturated with an emulsion of oil and gas in water, the oil and gas having been squeezed out of the muds below into these porous rocks, and remaining there in some mysterious way, instead of continuing their migration to the surface. Again I will observe that we do not see anything of the kind in nature—wells near the sea shore often striking pure fresh water (entirely devoid of oil or gas and even of salt water) in the recently formed sands or porous rocks beneath.

3. That the supposed gas and aqueous contents of incompressible strata or layers (page 741 line 12) which according to Mr. Daly could not previously be compressed out to the surface only a few feet or a few hundred feet away, are now (third phase of Mr. Daly's process) compressed laterally for miles and miles to finally accumulate into far-away oil and gas pools. Apart from the fact that these porous layers cannot be both at the same time compressible and incompressible, we know that porous sand layers form in the sediments disconnected lenticular beds seldom continuous over large areas; this would certainly stop the ingenious long lateral migration of Mr. Daly, and would send the oil and gas out to the surface and so would the faulting and fissuring in the highly disturbed portions of the mountain chain considered through which the oil and gas are supposed to migrate laterally. One certainly cannot admit that the shales covering the sands which, according to Mr. Daly's first phase of the process, could give out so easily their hydrocarbon contents have now become so impervious over distances of many miles, as to make possible this long lateral migration through the sands preventing all the while during this long travel the vertical escape to the surface only a few hundred feet away.

Mr. Daly says that "a partial origin of the rock pressure would thus have to be traced to orogenic deformation." This is rather vague and is only based on the remark that the pressure in Ohio and in Indiana, in the Trenton Limestone wells, was much smaller than in Pennsylvania and West Virginia; but we must not forget that the depths at which this gas was found in Ohio and Indiana were also much less than in the wells where the double pressure was recorded in Pennsylvania and West Virginia. As a matter of fact, the gas pressures in all fields are principally function of the depth indicating plainly the source from the volcanic magma below.

Mr. Daly's explanation of how capillary pressure seals an oil pool is ingenious, but may I ask why it only acts to prevent the pressure from dissipating outward into the surrounding sediments and why it did not also prevent the reverse movement of the accumulation of the gas and oil inward from the surrounding sediments into the sands?

F. G. Clapp, New York, N. Y. (communication to the Secretary.*)—The points of excellence in Mr. Daly's paper entitled "The Diastrophic Theory" are so numerous that it is unfortunate that he seems to have based his paper on a misunderstanding of the structural theory, as ordinarily understood. According to Mr. Daly, "the force which is supposed to have caused the motion is the gravity of the hydrocarbons." And again "Gravity or buoyancy is to be considered the sole agency through which accumulation has been brought about and, as such, is supposed to be adequate to explain accumulation under any condition of dip." So far as I know, no petroleum geologist believes these statements; so that Mr. Daly's paper must not be taken as a criticism of existing theories, but of his conception of them.

So far as I know, no petroleum geologist supposes the *motion* of the oil, gas and water in oil fields to have been caused by the force of gravity. To quote from an early issue of *Economic Geology*:[1]

"The 'anticlinal theory' is only one of the factors in the accumulation of oil and gas pools; and a geologist, in order to locate a pool, even approximately, has to consider every other particle of evidence found in structure of the subsurface rocks, changes in intervals, texture of the 'sands,' character of the overlying beds, differences in pressure, relations to water in the rocks, shape of the surrounding pools, and character of the oil in the vicinity; and every factor must be given its due weight, before a recommendation can safely be made. After all other factors have been considered, it might seem as if the 'anticlinal theory' has been lost sight of as unimportant; yet the fact remains that structure is the essential condition which finally determines the distribution and size of the pools when all other conditions are favorable."

Passing this technicality, however, we can wisely weigh Mr. Daly's remarks that oil fields exist only on the side of mountain ranges *away* from the source of pressure. Certainly this appears to be applicable in the case of the Appalachian fields, and might well explain several vexing questions; as, for instance, the absence of oil fields east of Pittsburgh, Pa., west of which they are so numerous. In this connection, it is important to raise several questions, as, for instance:

1. Why is natural gas found east of Pittsburgh in abundance, while oil is generally absent?

2. Why is gas found on the *inside* of the Transylvanian Basin in Hungary, while oil seems limited to the outside regions, in Roumania and Galicia?

3. How will this theory explain the presence of salt water in large quantities, in the regions away from the source of pressure?

* Received Aug. 28, 1916.

[1] F. G. Clapp's Discussion of paper of M. J. Munn, March, 1909, *Economic Geology*, vol. 4, No. 6, pp. 565–570 (September–October, 1909).

4. How about oil associated with faults, as in Oklahoma, California and Wyoming?

5. Can the diastrophic theory be effective in dips of ½° to 5°, in regions several hundred miles from any mountain belt or major axis?

While the theory as propounded may account for one cause of the movement of petroleum in certain directions, the question of whether this is the *main* cause of accumulation must depend somewhat on the answers to the above questions. In my opinion, they can not all be answered favorably to the theory. Of course, however, a mere theory of cause or origin can avail little in petroleum engineering. It is where the oil is found that counts. We know that it exists in definite types of structure, when these are affected by certain other modifying conditions; but that these same structures, with a different set of conditions, will hold no oil. Successful oil-location depends preëminently on *inference—i.e.*, a comparison of conditions in prospective fields with those in fields already known elsewhere in the world.

R. N. Pack, Washington, D. C. (communication to the Secretary*).—Mr. Daly's exposure of the frailties of the commonly accepted theories as to the mode of accumulation of oil is more acceptable than are most criticisms of this type, for after knocking our theories down over our eyes he does not leave us to grope blindly, but leads us to a brand new theory, both plausible and persuasive, that is to take the place of our old friends. Yet Mr. Daly's theory seems to be heir to some of the weaknesses characteristic of our old theories.

Most of the arguments that Mr. Daly raises against the anticlinal and hydraulic theories have been raised at one time or another by one writer or another, and there are probably now few geologists who will seriously contend that the force of gravity alone is adequate to accomplish widespread lateral migration of oil and gas, and the local accumulation of those materials in commercial amounts.

As Mr. Daly sees it, the chief failure of the anticlinal and hydraulic theories is that they do not take into consideration the effect upon the oil of the diastrophic forces that have affected the region. But most of the recent discussions of the origin of petroleum have laid stress upon the importance of these very forces, not, however, their importance as transporting agents, but as transforming agents, in changing the organic débris in the sedimentary beds into oil and gas. Mr. Daly tacitly assumes either that oil exists in the loose muds of the sea bottom practically from the moment of their deposition, or that it is formed soon afterward, during the period of compression due to sedimentation. In any case he appears to believe that oil exists in the sedimentary beds before they are deformed. However, until some well-authenticated

* Received Sept. 16, 1916.

examples of the formation of oil in unconsolidated sediments is brought forward, it would appear that the assumption that oil is formed in this manner is a less reasonable one to make than that oil is formed in part at least by the forces that caused deformation and perhaps local metamorphism. Of course it is possible that these forces not only have aided in the formation of oil, but also in its movement from one place to another; but it seems very unwise not to consider the first possibility at all.

Mr. Daly's discussion of the effect produced upon a prism of solid materials by pressure applied at the ends is interesting. After describing the purely theoretical example he applies the general principles involved to a succession of sedimentary beds, but in doing so he immediately agrees to consider only the upper part of the prism, that is, the part above the "neutral plane." One is led to wonder as to the depth this "neutral plane" lies beneath the surface, and just what the conditions are below it. Are the anticlinal axes the zones of contraction and the synclinal axes the zones of extension below this plane? If so, would oil, gas, and water tend to accumulate below the neutral plane in synclines rather than in anticlines? In the southern coast ranges of California many of the folds are shallow, and the "neutral plane" would in many cases certainly not be so very many hundred feet below the surface; so the question as to the accumulation of oil in them is not quite so academic as one might imagine.

According to Mr. Daly's theories, anticlines are important, so far as the accumulation of oil is concerned, only as they mark zones where the porosity is greater than in the surrounding region. In many of the California fields the folds are of variable character. Some are sharp and closely compressed; others broad and open. Between the two extremes almost any intermediate type may be found. It would seem natural to assume that along the more sharply flexed anticlines, the beds would be more fractured, or at least more extended, as Mr. Daly would say, and that they would thus determine the position of the more porous zones. Yet it is very frequently the case that it is not along these sharper folds that the oil accumulation is greatest at present, but in the upper parts of the larger, broader, and more gentle folds. Moreover, in the California fields the beds are so variable—so tremendously variable—that the differences in porosity due to lithology must be far greater than differences in porosity due to position along the folds; certainly the large broad folds can not have so altered the porosity of the bed that lithology will not still be the controlling feature. Yet in spite of this, the California fields offer a most splendid example of the occurrence of oil along anticlinal folds or in parts of the region where those folds dominate the structure. It would seem that there must be some other reason than increased porosity that causes the oil so to seek these structures.

If the forces that have caused the deformation of the region are the forces that have caused the migration of the oil and built up the pressure under which the oil and gas are now confined, one would expect that this rock pressure would be fairly constant over considerable areas. The field of action of these forces has been extensive, and, if we accept Mr. Daly's theory, these forces have swept the fluids from a wide area, segregated them, and collected them in out of the way corners. It seems hardly reasonable to suppose that if the rock pressure is due to such a general cause the fluid in one little corner would have a certain rock pressure, while that in a neighboring corner would be under another pressure that is radically different. Nor does it seem probable that within one little pool the pressure would vary greatly; yet in the California fields variation in pressure in a given stratum seems to be the rule rather than the exception. This variability may of course be explained in part by variation in lithology and other natural features, and also by artificial features, such as the mode of handling a well. It is not always the later wells that show the lesser pressure, so the variation can not be explained away completely as a decrease for the pool due to release by some wells. But even considering the factors that make for local variation, it seems that the differences found between wells only a few hundred feet apart are abnormally large.

Mr. Daly's discussion of the method by which an oil pool may be sealed is interesting indeed, yet it would seem that the very factors that he calls upon to seal up an oil pool and to maintain a given rock pressure might equally well be called upon to prevent migration originally. If a given force causes the oil to move through the rock pores and collect under pressure at a given place, and if the force ceases to be active, why will not the oil move back over the path it originally traveled?

According to Mr. Daly's theory the forces causing the oil and gas to migrate also caused the water to move. Indeed, he considers that the water moved carrying the hydrocarbons with it. Water, then, should be under the same pressure that the oil is under, as the force causing accumulation is the same, and the factors preventing dissipation the same for water as for oil. Yet in the California fields where water sands and oil sands are interstratified, no pressure comparable with the pressure in the oil sands is recorded for the water sands which lie between these oil sands unless a distinct flow of petroleum gas is noted with the water.

Mr. Daly notes the fact that in the Eastern fields there is an increase in rock pressure with the increase in age of the strata in which the oil or gas is found. The same can hardly be said of the California fields, for the greatest pressures noted occur in the younger beds which rest unconformably upon the shales in which the oil originated. The sands that are distinctly stratified with these shales contain oil under a much lower pressure.

In discussing rock pressure Mr. Daly points out that the chief explanations heretofore offered have been (1) that it is due either to hydrostatic pressure, (2) weight of superincumbent strata, (3) gradual accumulation of the inclosed gas, (4) capillary diffusion. He shows that some of these explanations are untenable, for the forces called upon are clearly not competent to have built up the high pressure now encountered. He therefore assumes that much of this pressure is due to the forces that have caused the deformation of the region.

An explanation that in many ways seems to be more reasonable is that the rock pressure is built up within the reservoir, not by the gradual concentration of gas, but by the change of some of the oil into gas. Also, perhaps by the same, perhaps by other reactions, heavy, viscous hydrocarbons are formed that so clog the rock pores that the movement through them of even the gaseous hydrocarbons is prohibited and the reservoir becomes sealed.

Rock pressure so developed would then have no direct relation to the pressure that originally caused the migration of the oil and it might be greater or less than that original pressure. Rock pressure need not be "fossil pressure," as one would be tempted to call it if one accepted Mr. Daly's interpretation.

Just what the reactions would be that would cause the formation of the gases within the reservoir can not be said, but as to those which result in the formation of the heavy viscous material there are a few more data. It is a pretty well known fact that, in the California fields, the highly mineralized water characteristic of the oil fields has a very pronounced effect upon the oil, and that where such water has entered the oil sands the oil in the vicinity is extremely heavy and tarry. This tarry material is in some places so viscous that it can not be pumped. Such material seems to be composed, in part at least, of oxygen and sulphur compounds and they seem to have been formed by the interaction of the hydrocarbons and the mineral salts in the water. This tarry material is quite competent to, and probably does, fill the rock pores and prevent the passage through them of the more fluid hydrocarbons.

MARCEL R. DALY (communication to the Secretary†).—The fundamental disagreement between Eugene Coste and the writer proceeds essentially from the contradictory views they hold on the origin of petroleum. This difference cannot be bridged, nor can inorganic and organic theories be discussed here. The writer has suggested that the proper thing in such a case would be to agree to disagree.

† Received Feb. 21, 1917.

Coming to the detailed objections further presented by Mr. Coste, the writer feels that, in the main, they take their source in a wrong interpretation of the theory, and the writer is sometimes too generously invested with views that are not his own.

1. The only requirement for the theory is that the oil proceeding from organic remains be distributed in a water-laden sediment, and that this sediment be submitted to the increasing compression due to the continuous accumulation of superimposed strata, which would tend to squeeze out the liquid contents (p. 748). This squeezing out would be further aided by the distortion of the strata (p. 744, *a*). Nothing here makes impossible the slow formation of the oil, if this is considered necessary, as the piling up of the strata in the syncline would require by itself a protracted length of time, and, further, the squeezing-out process is a slow one. Possibly the formation of the oil may even continue during part of the process of distortion. But the mode of formation of the oil and the time and temperature required for it are left to the chemist to decide. The diastrophic theory, which is essentially a theory of motion and accumulation dependent on the laws of mechanics, is not directly concerned with them, provided the general points heretofore outlined be agreed upon. Perhaps it would be wise not to claim too many "eons" for the formation of the hydrocarbons, if the statement made by Sir Boverton Redwood is correct that "the coral reefs of the Red Sea are charged in places with recent petroleum, formed in that torrid climate from the swarming organisms occupying the shallow pools."[1]

2. There is nothing mysterious in the tendency of the fluids, squeezed out from their original and heavily compressed layers, to congregate in some more porous or less compressed rock. This is a simple mechanical effect, from which there is no escape. A mechanical system reaches a state of equilibrium only when its potential energy reaches a minimum. It is for this same reason that water runs down hill, collects in bottoms, and does not run up hill again when so collected. Further, the squeezing out of the oil from the clayey layers becomes possible only by the deformation of the oil globules when compressed between the very fine particles of the clay; whereas in sandy layers this deformation would not take place to the same extent, on account of the greater volume of the grains and the corresponding enlargement of pore spaces. Here, the oil globules would return to their spherical form, by reason of surface tension, and would become trapped between the grains. A certain amount of the water contained in the sand layers may be replaced by the liquid containing the hydrocarbons. This portion would escape either through the overlying strata or laterally; water, on account of its lower viscosity and higher capillarity, being able to filter through where oil could not.

[1] *Petroleum* vol. 1, pp. 133–134 (1913).

The theory has never claimed that every sand would contain oil, nor that every mud is the parent matter from which oil proceeds.

3. I think that most of the objections contained in this paragraph would have been omitted if the critic had followed more closely the description of the process as stated by the writer. For instance, when it comes to oil migration, why does Mr. Coste hold the writer responsible for a transfer of the oil through "miles and miles" to "far-away oil and gas pools" under conditions admittedly adverse to motion, when the writer has specifically declared that "the extent of the movement would be variable in the extreme according to local conditions of the strata" (p. 749). In the same way, the writer has never claimed any state of incompressibility for the strata under consideration, and, above all, any general and absolute incompressibility for any stratum. Compressibility is essentially relative, and the whole theory is based on the production of zones of unequal compression. The writer has simply said that a layer of sand may become incompressible when it still contains a great percentage of holes and may thus act as a reservoir even under considerable pressure, which is a fact (p. 741). Further, Mr. Coste seems to have lost sight in his discussion of a well-known mechanical principle, which may be expressed as follows: When a material body is distorted by the application of two external forces, different in magnitude and direction, if one of the forces enters first alone into action and then both forces act together, the strains resulting from the application of the first force will be modified by the intervention of the second. This may be termed a superposition of effects. In such a case, an area which is compressed under the action of the first force may become decompressed and even stretched when the second enters into play. An illustration of this is a vertical column, first subjected to a load which compresses it, and later to a horizontal thrust which would bend and break it. In the same way, strata may be compressed vertically at a first stage, and later submitted to a horizontal thrust which would throw them into folds, changing entirely the distribution and the nature of the strains, and even opening fissures at the summit of the arches, if the superincumbent load is not large enough. If there is any fallacy in this case, it seems to belong to the commentator and not to the author of the theory.

The last sentence of paragraph 3 in Mr. Coste's discussion raises an interesting question. As the same question is asked by Mr. Pack, both will be answered together.

The writer concedes readily the difference between the original anticlinal theory and the structural theory propounded by F. G. Clapp, in which "the anticlinal theory is only one of the factors in the accumulation of oil and gas pools," which may become even "unimportant;" and he wishes it to be understood that his objections to the "anticlinal or structural theory" are exclusively limited to the "anticlinal" part of it.

The interpretation of the anticlinal theory itself given by the writer is not a personal conception, but an abstract of the interpretation of this theory given by W. T. Griswold,[2] in *U. S. Geological Survey Bulletin* 318, where the movement of oil in a porous stratum, completely saturated with water, is explicitly ascribed to buoyancy.[3] This conception has been severely criticised since by Malcolm J. Munn,[4] who seems to imply that there is yet something to disagree about in this direction. Although the writer is aware that this explanation of the motion of oil is losing ground every day, it is no less a fact that its influence is still felt in many text-books and papers of recent date. Expressions like these are frequently to be encountered: "If the rocks are thoroughly saturated, there will be a general migration of the globules of oil upward through the strata."[5] Or: "Petroleum . . . persistently climbs the slope of inclined water-containing strata."[6] Or again: "It is to be expected that in saturated rocks, petroleum, a liquid lighter than water, will rise to the highest parts of its container, the oil sand."[7] Quotations of this kind may be multiplied. They evidently imply a motion of the oil due to buoyancy; so that the old interpretation seems to remain in force at least in certain quarters.

It is the writer's opinion that the buoyancy of the oil cannot be interpreted as a direct source of motion of the oil on any reduced scale more than it can be on any large one. *Buoyancy simply does not move the oil.* It does not move the oil more than the weight of a stone moves the stone when transported by a current of water. It may *deflect* the motion imparted to the oil by hydraulic action, and, in this respect, its importance is enormous; but it stops there.

This deflective action would be adequate to explain mechanically such phenomena as the segregation of the oil globules during the process

[2] W. T. Griswold and M. J. Munn: Geology of Oil and Gas Fields in Steubenville, Burgettstown and Claysville Quadrangles, Ohio, West Virginia and Pennsylvania. *U. S. Geological Survey Bulletin* 318 (1907).

[3] W. T. Griswold writes as follows: "Oil and gas entering a porous rock that is completely saturated with water, will be forced up to the top of the porous stratum by the difference of the specific gravity of the hydrocarbons and the water. Here the oil and gas will remain if the porous stratum be perfectly level; but if it has a dip sufficient to overcome the friction, the particles of oil and gas will gradually move up this slope, the gas with its lower specific gravity occupying the higher places" (p. 14).

[4] M. J. Munn: Anticlinal and Hydraulic Theories of Oil and Gas Accumulation. *Economic Geology*, vol. 4, p. 509 (1909),; and more recently *U. S. Geological Survey Bulletin* 547 (1914), Reconnaissance of the Grandfield District, Oklahoma.

[5] C. T. Lupton: Oil and Gas in the Western Part of the Olympic Peninsula, Washington. *U. S. Geological Survey Bulletin* 581-B (1914), p. 79.

[6] K. C. Heald: Oil and Gas Geology of the Foraker Quadrangle, Osage County, Oklahoma. *U. S. Geological Survey Bulletin* 641 (1916), pp. 41–42.

[7] *Geological Survey of Canada, Memoir* 88 (1916), p. 169.

of migration, and the accumulation of the oil in places where the velocity of the current would be reduced, such as in convex arches along the dip or the strike of the sand (see latter paragraph), etc. But buoyancy without a current would not bring the result.

The writer is also of the opinion that, barring exceptional conditions, the velocity of ground waters would not be sufficient to overcome the resistances offered to the motion of the oil (p. 737). So that the motive force would have to be looked for elsewhere, and diastrophism seems to remain the only possible source to which we may apply.

Capillary action may promote the concentration of oil and gas in the sands, as explained by C. W. Washburne[8]; but the writer is not prepared to admit that it is the sole agent of such a concentration, and still less that it is the controlling factor of migration and accumulation of the hydrocarbons in pools. Its effects are related to the lithological character of the rocks and not to their structure; whereas everything points to an intimate relationship between oil or gas accumulation and structure. Further, capillary action would not account for rock pressure.

Coming back to the structural theory, the practical value of which the writer fully recognizes, we may ask: Is it a *theory* in the proper sense of the word, or is it not rather a statement of facts and conditions and a method for working out these statements in a practical way? A theory ought to be the philosophical explanation of the ascertained phenomena, thereby linking these phenomena together by some general principle. Where is the general principle to which the motion of oil and gas through the strata, their concentration and final accumulation in pools may be ascribed? It is precisely this "missing link" that the writer has endeavored to define. Whether his hypothesis, which is essentially a mechanical one, may be accepted, rejected, modified or perfected, remains an open question, and the criticism of men of the experience and knowledge of Mr. Clapp may do much to bring a final conclusion. In the mind of the writer, the merit of the diastrophic theory—if any—does not consist so much in the theory itself, but in the direction of research it opens to future investigators. The writer feels that the importance of mechanics in the interpretation of geologic phenomena cannot be overestimated. After all, everything in Nature obeys the laws of mechanics, and most geologic phenomena are nothing else than the expression of these laws.

The practical usefulness of any general theory that would definitely establish the laws that govern the motion and accumulation of the hydrocarbons is obvious. Today, using Mr. Clapp's expression, "successful oil location depends preëminently on inference." But an inference is a hypothetical induction built on the comparison of ascertained facts in every specific instance. Undoubtedly, an ascertained law would be a

[8] *Trans.*, vol. 50, p. 829 (1914).

time and money saver in the field; when the true causes of a phenomenon are fully understood, it becomes less difficult to anticipate the conditions under which it may be repeated and to determine on the ground the places where such conditions are to be found.

Coming to the questions asked by Mr. Clapp, and numbered 1 to 5:

Questions 1, 2 *and* 3 may be answered together, as the facts stated would be derived, under the diastrophic theory, from the same cause. Without going into details, the writer wishes to say that he has been brought to foresee the following general law: "Whenever an oil-bearing region is folded by a simple dominant thrust or repeated thrusts in the same direction (Appalachians, Carpathians), the fluids inclosed in the strata, and which are put in motion, will have a tendency to collect ahead of the line of application of the thrust, and to segregate in successive deposits of increasing density, or decreasing buoyancy, with the increase of distance from this line." This implies that gas would tend to accumulate nearest to the line of thrust; oil, farther from it; and that water may reach still farther away.

The first part of this law would result from the application of a principle which has been called upon several times in this paper; *viz.*, when a mechanical system is in equilibrium, its potential energy is a minimum. So that fluids will have a tendency to migrate from the zones of higher compression—or of higher potential—toward the zones of lower compression—or of lower potential—*viz.*, away from the source of pressure.

The second part of the law would be a consequence of the same principles which regulate the deposition of bodies heavier than water in a current of decreasing velocity.

Let us consider the simple case of a horizontal current of water, in an inclosed channel, provided with a steady motion and a progressively decreasing velocity from A to B (Fig. 1); the decrease of velocity being due to a progressive increase of the width of the channel. Let us imagine that several bodies heavier than water, of varying densities but individually of the same shape and volume, are at first collected in A. The motion of the water will tend to carry them downstream, toward B. The transporting power of the water will depend on its kinetic energy ($\frac{1}{2}mv^2$), or its capacity to do work; and as same volumes and shapes are considered, and as the mass of the water per unit volume remains constant, this energy will vary only with the velocity of the current.[9] If

[9] Du Buat has shown that when a body is at rest in a moving fluid, if the motion is steady and the flow takes place in a pipe, the pressure R exerted by the water against the body may be expressed by $R = M \frac{mv^2}{2} S$, in which v is the undisturbed velocity of the stream, m the mass of the water per unit volume, S the projected area of the body on a plane normal to the direction of flow, and M a coefficient depending on the shape of the body and its relative proportions with the transverse section of the pipe (M. Bresse, *Cours de Mécanique Appliquée* 2e P.-*Hydraulique*, p. 429). According

the velocity increases, so will the transporting power; and, conversely, a reduction of velocity will mean a decrease of the power of transportation. Now, the specific gravity of the materials has a marked effect upon the mean velocity necessary to move them. Bodies heavier than water, like stones, would move along the bottom of the channel by rolling, sliding, or more generally by a succession of leaps; *viz.*, rising from the bottom and returning to it after having described a curve in the water. It is essentially gravity which causes the resistance through which the kinetic energy imparted to the materials by the water is thus spent in friction or collisions. So the greater the gravity, the greater the requisite mean velocity of the current.[10] The result is that to each material there corresponds a minimum velocity under which transportation is no more possible, and that each material will be dropped at the point where the corresponding minimum is reached. A mechanical segregation will ensue, whereby the respective distances of transportation, from the point of origin to the point of deposition, will increase as the specific gravity of the body decreases.

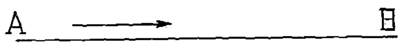

FIG. 1.

Let us repeat the same process with bodies of varying shape and volume, as well as of varying gravity. For each series of bodies of same gravity, the increase of volume will cause a corresponding increase of resisrance to motion;[11] and the mean velocity required for the motion will

to Lord Rayleigh's theory (*Philosophical Magazine*, December, 1876), if a plate with parallel edges be held in a stream normally to the direction of flow, the mean unbalanced pressure on the body is $= 0.88 \frac{mv^2}{2} S$, where the letters have the same signification as above. Both formulæ show that the power of transportation of a current of water is, at the same time, a function of the kinetic energy of the water ($\frac{1}{2}mv^2$) and of the shape and volume of the body transported (S). If these last two factors are supposed to be the same for the different bodies considered, as m is a constant, the intensity of the force of motion will simply vary, in each case, with the square of the velocity of the current.

[10] Chailly gives the following formula for finding the velocity required to move rounded stones or shingle: $v = 5.67\sqrt{a \cdot g}$ where v is the velocity of water in feet per second; a the average diameter in feet of the body to be moved; and g its specific gravity. The velocities required to move such bodies of the same shape and volume, but of varying densities, would thus vary as the root of their specific gravities.

[11] Du Buat's formula shows that the pressure exerted by the moving water against a body at rest and immersed in the current, is proportional to the projected area of the body on a plane normal to the direction of flow. For a spherical body, the projected area would vary as the square of the radius of the sphere and the weight as its third power. Weight, hence resistance to motion, in the case of bodies heavier than water, would increase more rapidly than the projected area, hence than the motive force. As solid bodies transported by a current are more or less rounded after a short time, the same relation is approximately true for them, if we consider their mean radius.

increase with the volume. The bodies will thus be deposited at distances increasing as their volume decreases. There will be, not a *point* of deposition for the bodies of like gravity, but a more or less extended *zone;* and the zones of deposition of the series of different gravities may encroach on each other.

Experience agrees with this interpretation. For instance, the principle is used in ordinary gold washing, or for the assortment of sands of like size but varying specific gravity, etc. Worded as it is, this interpretation applies only tó bodies heavier than water; but it may be shown that, with a simple modification of terms, it may be extended to bodies lighter than water; or, in other words, that the same law regulates the order of deposition of materials of any gravity in a steady current of decreasing velocity flowing through an inclosed channel.

We may remark that the action of gravity which creates a resistance against motion is not really represented by the specific gravity of the material (ratio of its weight to that of an equal volume of water), but by the difference between this specific gravity and the specific gravity of the water; for a body immersed in a fluid suffers a loss of weight which is equal to the weight of fluid it has displaced. If δ be the specific gravity of the body, and if the specific gravity of water is taken as a unit, the resistance due to gravity is a function of $(\delta - 1)$ and not of δ. In the C.G.S. system $(\delta - 1)$ would express a density. For lack of a better expression we may term it the "density in water" of the body. Now, this particular density may have a positive or a negative value, depending upon whether δ is greater or smaller than unity. If positive, the action of gravity will be directed down; this is the case of bodies heavier than water. If negative, the direction will be up, and the "density in water" becomes the buoyancy of the body per unit volume. In either case, the resistance to motion may be explained along the same lines. But the bodies will either drop to the bottom of the channel or be raised against its roof, depending upon whether δ is greater or smaller than unity. It may be remarked further that the absolute value of $(\delta - 1)$, when $\delta < 1$, decreases when δ increases; or, in other terms, that the numerical value of buoyancy decreases when the density of the body, that is lighter than water, increases; and the buoyancy of a body having the same density as water would be equal to zero. A general law may then be expressed, which would be applicable to all materials, whatever their gravity: "When a flow of water takes place in an inclosed horizontal channel, with a steady motion and a decreasing velocity from one end to the other, material bodies of varying specific gravity, shape and volume, will have a tendency to segregate and to be deposited at distances from the point of origin which will increase as their respective 'densities in water' $(\delta - 1)$ and their respective volumes decrease."

Applying this law to oil and gas transported in a current of water under the conditions stated above, we find that: (*a*) oil would have a tendency to segregate from the gas; (*b*) it would have a tendency to be transported and deposited farther than the gas from the point of origin.

But there are several factors that have not been taken into account in the preceding simplified theoretical instance. The chief ones may be enumerated as follows: (1) The motion will not take place in an inclosed channel, but through many irregular and capillary channels, and the resistances to motion will vary, not only according to density, shape and volume, but also according to the individual nature of the bodies transported (viscosity, surface tension, etc.) and the local texture and porosity of the "sand." (2) The strata through which the flow takes place will not be horizontal, but flexured. (3) The materials would not proceed, as a whole, from the same point of origin, but would be first in a state of irregular dispersion over a more or less wide area, from which they would have to be collected by the current. (4) Some chemical or physical changes may occur: gas may evolve from the oil during the process of migration through the sand, as well as in the final area of deposition (reservoir), whether it be dissolved gas released by the reduction of pressure, or gas produced by chemical action (?).

It is not possible to discuss here in detail the effects that such a set of conditions would entail; and the lack of experimental data as well as the complexity of the problem does not allow a definitive conclusion. But a careful investigation of the nature and probable influence of the intervening factors has led the writer to believe that the tendency toward segregation of the materials (oil and gas), as well as to their relative order of deposition, would still obtain. Only, for each material the zone of accumulation instead of being unique, may be repeated several times in succession; for the velocity of the transporting water would pass through a series of maxima and minima, and the minimum velocity required for the deposition of this material may be encountered more than once. Further, these zones of accumulation, instead of being limited to reduced areas, would become zones of more or less great extent, and the oil zones and gas zones would sometimes encroach on each other. The water zone—the water being in large excess—would extend all through, with or without local interruptions.

In Pennsylvania, at least for oil and gas, the rule holds good (question 1). As Mr. Clapp remarks, "natural gas is found east of Pittsburgh in abundance, while oil is generally absent." The thrust would have proceeded here from the southeast, and the first pools encountered, when we start from the line of application of the thrust and follow in the direction of the movement of deformation toward the northwest, are gas pools. The oil pools are mostly farther west and northwest; Pittsburgh happening to be nearly on the dividing line. This distribution is exactly what should be expected from the law. It is further interesting to note that the gas and oil regions (zones of deposition) encroach sometimes on each other, as may be seen by the inspection of the map, and this too would agree with the conclusions of the writer.[12]

In the fields of central Europe (Galicia, etc.) (question 2) where at least two consecutive thrusts in the same direction have taken place, the results are more obscure. But, here again, it seems as if oil would be ahead of gas. Transylvania occupies the central portion of the sector of which the Carpathians constitute the arc, and gas is found in this section at many points of the basin drained by the Maros River and its tributaries east to the Hargitta range, and by the Szamos river northward, while oil is mostly found farther north, east or southeast, in the outlying region. The general disposition seems to follow here closely the disposition of the fields of Pennsylvania, and probably for the same reasons.

As far as salt water is concerned (question 3) the writer has shown that the water should reach farther away than the transported materials (oil and gas). This is evident from the fact that these materials would be dropped from the current when the minimum velocity which would allow their motion, was reached. But water itself would continue to move until its own speed was reduced to nil. So that it becomes possible to imagine the formation of "pools of water," ahead of the region of oil and gas, and farther from the line of application of the thrust. Originally, the pressure of the water in such pools would have been due to diastrophic pressure, less the loss of head encountered. But the "keeping up" of such a pressure on water alone would be very questionable on mechanical grounds. By reason of its reduced amount of compressibility,[13] water is a bad accumulator of pressure, unless it is held in an absolutely tight container, like the cylinder of a hydraulic press. But terranes are not so tight, and such a pressure would soon disappear. If then, pressure is ever found to exist in a "water pool," ahead of the oil and gas regions, and if such a pressure can not be traced to static pressure due to artesian action, it must indicate the presence of some oil or gas reservoir with which the water would be in communication, and that would act as an accumulator for the pressure. It would not be necessary, in such a case, for the accumulator to be located in the immediate neighborhood of the water pool, as pressure may be transmitted by water itself through underground channels, the same as it would be through a pipe from an ordinary compressor.

Questions 4 and 5.—In order to answer these, it will be useful to enter into some more details of the mechanical process of deformation and of

[12] M. L. Fuller: The Gaines Oil Field of Northern Pennsylvania, 22nd *Annual Report of the U. S. Geological Survey* (1902), Plate XXXVI, Map of oil and gas fields of Pennsylvania, opposite p. 579.

[13] Regnault, Grasset and Cailletet give about 50 millionths for the compressibility of water at 0° C., for one atmosphere of pressure.

the migration of the fluids as interpreted by the writer. This part has only been sketched in the preceding paper.

Let us imagine a prism composed of a series of horizontal strata, submitted to a lateral horizontal thrust, acting in the direction of the arrow (Fig. 2). For the sake of simplicity, we will suppose, at first, that the strata are continuous, individually homogeneous and of equal thickness all through, and that the superincumbent load is distributed in a uniform way; further, we will consider only this part of the prism that is situated above its theoretical neutral plane. We have seen (p. 743) that, under such conditions, the prism will be deformed, if the thrust is of sufficient magnitude; that the deformation will begin first along the line *AA* of application of the force, and, by and by, will reach farther away from it, giving rise to successive waves or longitudinal bends (anticlines and synclines) normal to the force, more or less parallel to *AA*, and de-

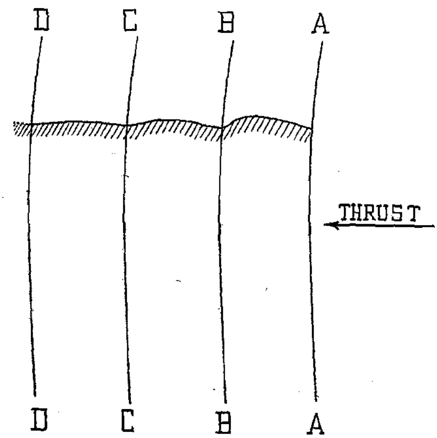

FIG. 2.

creasing in importance the farther we reach in the direction of the arrow; and, finally, that the rate of the compression to which the different points of the prism are submitted will follow a similar law, decreasing in a general way as their distance from *AA* increases, but presenting a wavy succession of maxima and minima, the maxima corresponding to the synclines and the minima to the anticlines. The whole prism may be divided into zones, individually elongated in a transversal direction to the prism and parallel to *AA*, in which the amount of compression and of deformation obtained are greater the nearer the zone stands to the line *AA*.

The first consequence is that the fluids inclosed in the strata would be put in motion *as soon* as the deformation itself begins, and that they would move from the areas of higher pressure toward the areas of lower pressure, *i.e.*, away from the thrust. But a time may arrive at which the elasticity of the compressed material of the strata in the first zone *AABB* will be overcome; the material, unable to satisfy any longer the accumulated stresses by simple bending, will give way, and ruptures or crushings will occur. These disruptions will not take place at the same time at every point, as the active forces and the resistances would never be equally distributed everywhere; but the material will give way in succession at points irregularly distributed along this zone, and these points will become as many *centers of impact,* transmitting a sudden pressure to the inclosed liquids. This will be renewed again and again, until compression has reached its maximum effect, for the time being, in the zone *AABB, viz.,* until the accumulated stresses have been everywhere satisfied by deformation in this zone, and a new temporary equilibrium obtained. From this moment, the principal effect of the deformation will be transferred to the next zone *BBCC*, where the same succession of phenomena may take place; then to *CCDD*, etc. *So that while AA remains, throughout, the line of application of the thrust, the zone of active deformation, or the zone of the centers of pressure, will progressively move away from it in the direction of the thrust,* and this displacement may continue as long and as far as the thrust itself continues to operate. It may thus reach considerable distances, with an ever decreasing effect, until it dies out.

The same process will be repeated many times. Stresses will constantly accumulate in the zone *AABB* and new disruptions will follow, that will spread out, from place to place, or from zone to zone, away from the thrust, until they reach the limit of the deformed area. The region will thus be gone over repeatedly by *waves of deformation* that will follow each other in succession and gradually decrease with the distance, as ripples do in a still water where stones are dropped at intervals from the same point.[14]

It may be stated here immediately that this process would not imply, as a necessary consequence, a migration of equal importance for the fluids transported (oil and gas). On the contrary, we will see that migration may sometimes be very limited in extent. But the compressed region as a whole would be, under the simple conditions admitted, progressively combed of its transportable material, the combing process following the direction of the movement.

Let us now return to the moment of our description where the compressed rock material is giving way along the zone *AABB*. We have seen that disruption would take place on different points of the zone in irregu-

[14] The resulting motion imparted to the liquids would thus become essentially discontinuous and the transportation of the material from one point to another would be composed of a succession of independent stages. But during each of these stages, the motion of the current may be considered as steady or as constituted of a succession of steady motions, with a sufficient degree of approximation.

lar succession, creating successive centers of impact. Let us consider one of these centers, O, which may be situated on any line NN parallel to the line AA of application of the thrust (Fig. 3). The fluids inclosed in a given stratum, compressed at the point O, will be pushed forward in the direction of the arrow. But this movement will not take place simply in a straight line, normal to NN; it will be fan-shaped, and the surface covered by the liquids in motion will take the form of a sector, whose center will be in O. The cross-section of the stream will thus increase progressively in the direction of flow, and if the resistance to motion is uniform, as in our simplified case, the velocity of the liquid will progressively decrease away from the thrust. The points of equal mean velocity $v_1, v_2, v_3, \ldots$ written in a decreasing order, will be distributed along concentric arcs of circles, of successively increasing radii. If now the same process is followed for every point of the line NN, and the points

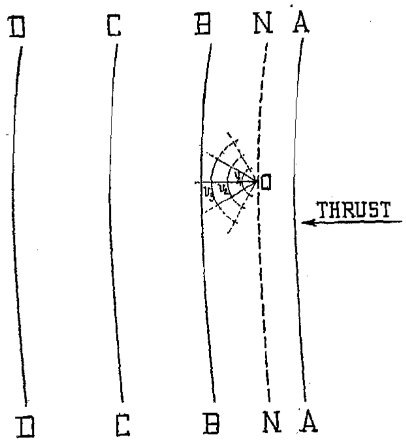

FIG. 3.

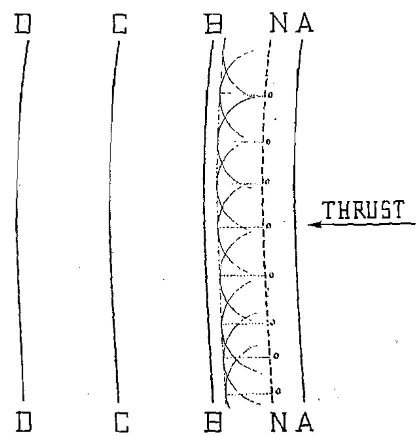

FIG. 4.

of equal mean velocity $v_1, v_2, v_3, \ldots$ are marked on the normals to this line, these points will be found to be located on the envelopes of the corresponding circles, *i.e.*, on lines parallel to AA (Fig. 4). And the mean velocity of the sheet of liquid displaced, when considered in its entirety, will be found to decrease progressively along the direction of flow, *although the motion may not take place everywhere at the same time.* This will be true whatever the position of the line NN in the zone. So that every particle of the liquid contained in the zone and which is put in motion, will successively reach the velocities $v_1, v_2, v_3, \ldots$ along more or less narrow strips parallel to AA. If then, among these velocities should be found the minimum velocity beyond which the transportation of a given material ceases to be possible, this material would be deposited along the corresponding strip. In other words, the general trend of the deposits would be parallel to the line of application of the thrust.

Precisely there is a factor which determines such a reduction of velocity and fixes the location of the strips of deposition; this is the factor of structural deformation. If, instead of considering the single zone *AABB*, we would consider a series of such zones in succession, they would present in section the appearance of Fig. 5. The synclines being compressed more than the anticlines, each syncline individually becomes a center of pressure, whose importance decreases away from the thrust; and these centers will act as relays in the movement of the liquid. Between two relays, the velocity of the liquid would decrease when the stream passes over the arch; for the reason that the raising of the liquid from a lower level to a higher one and the sudden increase of the section or of the number of the channels of flow, when entering from a less open to a more open portion of the stratum, would cause a loss of head and an increase of the total section of flow, hence a reduction of speed. When the arch had been passed, the velocity would again tend to increase when the liquid enters the following syncline; but this new rate of velocity

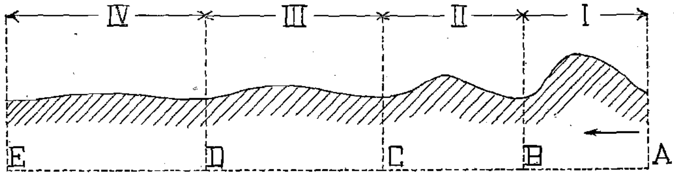

FIG. 5.

would be inferior to the one obtained in the preceding syncline, by reason of the loss of head encountered and the progressive reduction of the compression away from the thrust. So that the velocity of the current would diminish away from the thrust, but would at the same time present a succession of ever-decreasing maxima and minima, the maxima corresponding to the synclines and the minima to the anticlines or arches.

Now, with the progressive increase of compression and consequent increase of deformation, an anticline would progressively increase in height, and the difference of porosity between the summit of this anticline and the bottom of the preceding syncline would increase also.[15] So that the loss of head itself would tend to increase and the velocity of flow to decrease. Thus, the velocity of the flow passing over the arches would become lowered in the course of time, during the process of deformation, and it may reach the velocity-limit corresponding to deposition before this limit is reached on any other point of the line. The summits of the arches become in this way the natural loci of deposition.

[15] The anticlines considered here are the anticlines of the Appalachian type. Forms exaggerated by compression would give a different result. But it must be remembered that the case under treatment is the simplest possible one.

As the arches themselves are parallel to the line AA of application of the thrust, so will be the final deposits or pools.

The same result would obtain with monoclines and the rims of terraces. These forms mostly represent a stage of incipient flexure farther away from the thrust, especially when the strata are slightly bent downward, as in a basin of deposition. And again, the same process would explain why changes in the direction of the strata along their strike may cause local concentration of the material. We have seen that the flow issuing from a local center of pressure would be diverging in direction (fan-shaped). When a line of strike is encountered, any velocity which is not normal to it may be decomposed into two components: one normal to the strike, and the other tangent to it. The first would move the liquid along the dip, in a vertical plane; the second would move it along the strike, in a horizontal one (Fig. 6). And the horizontal incurvation of

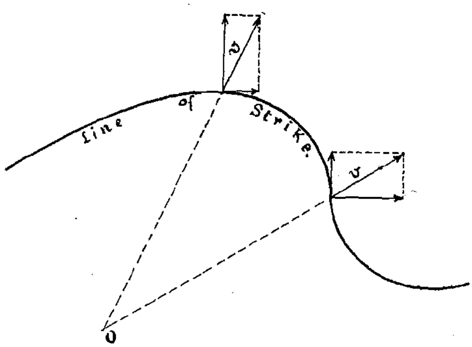

FIG. 6.

the strike may bring about local reductions of velocity (conflicting currents, etc.), and consequent areas of deposition.

It is evident that the extent of the migration of any transported material (oil or gas) under the conditions described, would depend primarily on the distances at which two successive zones, presenting the velocity-limit necessary for the deposition of this particular material, may be encountered. Between two such zones, the territory would be combed of the material—if any; but such material need not go farther than the second zone. *Transportation and concentration, or migration, becomes, under this conception, an essentially local phenomenon* in the affected area, which may take place independently on different points of the field, either at the same time or at another. This, in contradistinction with compression and deformation, which are phenomena of a general order, that would follow the laws of continuity throughout the field.

In developing the preceding theory, the writer has had in view the simplest possible conditions, and it may be objected that such conditions are nowhere to be encountered at the same time on any extended area. This is readily conceded. The number, direction, relative importance, and age of the successive deformative movements to which a region has been submitted, may vary widely, inducing consequent irregularities in the distribution, extent, nature and physical conditions of the layers. Lateral variation will be the rule in any stratum, and unconformities may occur between the series. Simple flexion may be complicated by the sliding of the beds; structural forms exaggerated by compression; faults and other tectonic accidents or even igneous intrusions may occur. Finally, changes may take place subsequent to deformation and accumulation, such as a change in the local level of the waters, etc. But whatever the conditions may be, the whole trend of the observed phenomena will have to be underlain by the same general principles of which the writer has tried to make an application; for these principles are not relative, but partake of the independent reality of the laws of mechanics. Only, the result will be that of a superposition of effects and may be complicated accordingly. Thus, when the geologist would come to locate an oil region, or simply a pool, under the diastrophic theory, he would not be exempted from considering every particle of evidence any more than he is today under Mr. Clapp's structural theory; but he would at least be provided with a few comprehensive laws, which would allow him to anticipate the general trend of things, to seriate the intervening factors according to their probable rank of influence, and finally to reach a conclusion based not only on inference, but on a logical process of reasoning, where deduction would come to the help of induction.

It now becomes possible to answer the further questions proposed by Mr. Clapp.

(*Question* 4). If the writer interprets Mr. Clapp[16] correctly there are many cases in which oil is found on both sides of a fault crossing a productive field, and the question is: how is oil to be found *on both sides* of the fault, as, for instance, in Oklahoma, where such faults are assumed to be thrust faults.

To this, the following answer may be made. According to the views of the writer, heretofore presented, the movement towards accumulation keeps pace with deformation and accumulation begins as soon as in the future reservoir the velocity of the transporting waters reaches the minimum under which transportation is no more possible. In a simple flexure (anticline or terrace) accumulation may begin and may even be completed long before the limit of deformation has been attained. On the other hand, a fault, especially a thrust fault, is generally one of the last expressions of deformation. When a stratum is compressed tangentially its tendency is to bend before breaking. Thus, compression may first accumulate the hydrocarbons in a reservoir and only later break through this same reservoir with a fault, after the accumulation has been com-

[16] From correspondence with Mr. Clapp.

pleted. According to the relative position of the fault and of the reservoir, the hydrocarbons would be found either in the front, in the rear, or on both sides of the fault. The last case, where the fault cuts through the reservoir, would naturally be the most frequent, as the location of both the reservoir and the area of maximum local stresses would be nearly coincident. This would appear the simplest and most probable explanation of the facts. In the case under consideration, the oil deposit would antecede the faulting, in the same way as the coal seam antecedes the fault which has displaced it.

(*Question* 5). We have seen that a distinction must be made between the line of application of the thrust and the zone of active deformation or the zone of the centers of pressure. The former's relative position in the deformed area remains constant during the process of deformation, whereas the second would move away from it progressively, in the direction of the force. Concentration and accumulation may thus take place as far as deformation remains effective, provided the other conditions (existence of oil and gas in a disseminated state, presence of water, porous layers, etc.) are favorable; and the distance attained is limited only by the extent of the area of deformation itself. On the farthest borders of such an area, where the effects of compression would be reduced, the velocity of the transporting waters would be reduced in proportion, and the velocity-limit necessary for deposition may be reached with dips smaller than elsewhere. But it must be remembered that the remoteness of the "mountain belt" or the "major axis" from the point of accumulation, would have no bearing whatever upon the distance covered by the migration of the hydrocarbons. As previously stated, migration is essentially a local phenomenon.

Answering Mr. Pack, it is not the intention of the writer to assume that the oil existed in the original strata where the parent matter was at first deposited (in lagoons, marshes, deltas or at the bottom of the sea) from the moment of the deposition of such parent matter or even soon afterward; and the writer readily admits that the transformation may have occurred not only during the time of accumulation of the sediments in the syncline, but even during part of the movement of deformation itself. But, as already stated, this point is immaterial for the theory, which is interested in the genesis of the oil only in so far as the mode of formation concedes a first state of dissemination of the hydrocarbons in a water-laden sediment, submitted to increasing vertical pressure and subsequent lateral thrust or thrusts.

It frequently happens that, from the start, it is not possible to attack a problem in its more complex form; and this is especially true when we try to submit natural phenomena to mathematical treatment. The number of the factors that would affect the results, their intricacy, and, let us say, our ignorance of their real nature and true mode of action, is such as to put any solution out of reach, unless we consent to reduce the problem to its simpler lines and to consider, at first, some well-defined and better-known specific instance. The writer is aware of the inconveniences and of the danger inherent in such a procedure, but, unfortunately, it is the only one at our disposition. If the results are not always entirely satisfactory, it is no less true that the solution of a specific case may open our eyes to the general direction of things, exactly as the knowledge of a curve between narrow limits may give us a glimpse of the class to which it belongs.

Among the known oil and gas fields, the Appalachian belt seems to the writer to present one of ideal qualities. Here, the structure is relatively simple and has been well worked out; the principal folding has taken place at one defined period and under the influence of a single dominant thrust; and later disturbances have not obscured the results. In this region, the thickness of the strata involved justifies us in considering the oil sands as located above the theoretical neutral plane, which simplifies the treatment, and the gentle anticlines offer a simple feature of distortion. These conditions render an easy analysis of facts and application of mechanical principles. Mechanical laws are absolute, and if they are true in one field, they are equally true in any other. They simply need to be applied with proper data and proper judgment. We concede that sometimes conditions may be confusing, as in the South Coast Range of California, where the folds are often shallow, as Mr. Pack remarks, and where, further, two different sets of thrusts, acting from two different directions, may have to be considered. But liquids will always tend to move from zones of higher to zones of lower compression; for every material transported in a current of water, there will be always a velocity-limit under which transportation is no more possible and deposition ensues; distorted strata will always obey the general laws of distortion; and the mechanical reasons which have brought the writer to consider diastrophism as the principal motive power and water under hydraulic action as the transporting agent, will remain the same. As in an equation, you may have to change the coefficients; the fundamental value of the equation remains.

Let us state here, incidentally, that forms of distortion, like an anticline, may present zones of porosity at one time and not at another. An anticline may be said to begin with the smallest incurvation of a stratum and it may end in a flattened isoclinal fold, overturned or not, faulted or thrusted or not. Between the extremes, all kinds of intermediate forms exist, in which the internal structure of the material would not be the same, and the conditions of porosity would vary accordingly. These would even vary for any given anticline during the folding process. What the writer has said about anticlines must be understood to apply to the anticlinal ridges of the Appalachian type, which he had in view, but not to forms exaggerated by compression.

It is true that anticlines of the aforesaid type are important, in so far as the accumulation of oil is concerned, as zones of greater porosity; a container is always needed to hold the contents. But this is not the sole function of an anticline, nor is the anticline the sole possible container. This has been pointed out by the writer.[17] Convex edges or arches along the dip or the strike of the strata may be good places for accumulation in general, as these would result in a reduction of the velocity; and buoyancy, whose real function seems to appear here, would act as gravity does when a slackening current of water drops its load: only the action would be reversed. Buoyancy would deflect the direction of motion upward and the hydrocarbons would become trapped under the concave or vault-like portion of the strata.

The lithological character of the strata may have much to do in the way of easing or impeding the circulation of the liquids; but an extensive layer with the same lithological character, the same thickness and the same dip throughout, probably would not be a favorable place for accumulation, as it would offer poor chances for an abrupt reduction of motion, which seems to be an essential factor of deposition or accumulation. It is precisely where "folds dominate the structure" that the best conditions of deposition ought to be found.

There is no mechanical reason why rock pressure, as the writer understands it, should be fairly constant over considerable areas in an oil or gas pool; but there are reasons why it should *not* be so. According to the writer's views, rock pressure in oil or gas pools is essentially due to the original pressure of deformation, less the loss of head encountered on the way, plus a certain possible amount of added pressure due to progressive gas increase.[18] Now, an oil pool or a gas pool cannot be compared to a gas holder or to a reservoir for water under constant pressure. In a gas holder, the gas is at the same pressure everywhere, and in a reservoir under constant pressure, water is at the same pressure on the same horizontal level. For the reason that, in the first case, gas molecules can move with an equal freedom in any direction; and, in the second case, water molecules have an equal freedom of movement in all directions of the same horizontal plane. But a gas pool or an oil pool is formed by the juxtaposition of an indefinite number of cells, intercommunicating in the most irregular way, and equal freedom of movement is not permitted in any direction. Further, the resistance to motion between cells is variable, and the resistances accumulate with the distance between points. So that, even barring the possible additional pressure due to irregular gas increase, the original pressure due to deformation would not have to be the same at all points, as the loss of head would be at variance; and no balance could be reestablished between points, in the

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[17] See pp. 739, 749.

[18] *Idem.*

course of time, as the resistance to motion between cells would remain the same. The conclusion is that rock pressure, under the diastrophic theory, must vary, as a rule, from one point to another in an oil or gas field, and the theory agrees once more with the observed facts.

Mr. Pack, in common with Mr. Coste, remarks that the very factors that the writer calls upon to seal up an oil pool and to maintain a given rock pressure, might equally well be called upon to prevent migration originally. To this it may be answered that conditions in both cases are entirely different. In an oil and gas pool, the rock pressure is essentially static; whereas, during the process of migration, the motive pressure would be dynamic, the transporting agent being water acting under a ram effect. As an illustration in the case, you may consider the following test: try to drive a nail in a board simply by the weight of the hammer bearing on the head of the nail, and then drive the nail by a blow. The difference is apparent at once. The first case is a case of static pressure; the second, that of dynamic action. There are other differences, all in favor of the process of migration: Rock pressure is only a remainder of the pressure to which migration is due; again, the "tubes" of the capping rock which holds the gas would be of a subcapillary size, instead of being capillary as the channels of the sand strata through which the movement toward accumulation takes place, and the resistance offered by the Jamin tubes is in the inverse ratio of their diameter; then again, original oil would be in a state of disseminated particles in a matrix of water, instead of being in the state of a more or less continuous mass, as in an oil pool, etc.

Oil which has moved through the rock pores and has collected under pressure at a given place, would not move back over the path it originally traveled any more than the nail which has been driven in the wood would be thrust out of the board. Static pressure would be unable to undo here what repeated dynamic action had caused to be.

The fact that "in the California fields, where water sands and oil sands are interstratified, no pressure comparable with the pressure in the oil sands is recorded for the water sands which lie between the oil sands, unless a distinct flow of petroleum gas is noted with the water," is easily explained, in accordance with physical and mechanical laws, as a consequence of a common original diastrophic pressure. Let us note first that Mr. Pack's remark implies that whenever there is a difference in the pressure between an oil sand and a water sand, there is an intermedial layer between both sands which is impenetrable to this pressure, or else the balance of pressure would be soon reëstablished. The conclusion is that the pressure in both sands is independent. Now, let us suppose that, at a certain moment, the same amount of pressure should be imparted to both sands, as would be the case if these layers were submitted together to a common diastrophic pressure; and, for the sake of simplicity, let us consider the temperature as constant. Liquids are compressible only in a very small degree; which means that a very small reduction in volume would correspond to an enormous increase of pressure, and, conversely, that a very small expansion of volume, at constant temperature, would allow a very great reduction of pressure. Whereas gases are essentially compressible, and a great increase of pressure, at constant temperature, would only be reached by a corresponding large decrease of volume; or, conversely, the volume would have to be largely increased to decrease the pressure to any serious extent. Gases are thus good accumulators of pressure, where liquids are not. As oil would always be in relation with some gas, an oil sand would become a good accumulator of pressure also; but a water sand would not, unless accidentally put in direct relation with the gas. On the other hand, strata, especially Tertiary sediments, are never absolutely tight, and a very small expansion of the water body would rapidly reduce the pressure to the normal; whereas oil strata, containing gas, would be in a very much more favorable condition to retain a large part of it.

The fact pointed out by the writer in reference to the increase of rock pressure with the depth—or age—of the strata in the Eastern fields (Appalachian belt), is not contradicted by this other fact that the situation seems to be reversed in some Californian fields, where greater pressures are noted in younger beds resting unconformably on older rocks; as the tectonic conditions would not be the same in both instances. In the first case, the whole pile of sediments has been involved in the same deformative movement, due to a single dominant thrust, and, therefore, the result is simple and follows the law of continuity; whereas, in California, deformation has been due to several thrusts, acting at different periods, in different directions, and it has affected unequally the unconformable series. The mechanical law of the superposition of effects, to which the writer has previously referred, may have largely interfered in this case, and its influence would have to be defined.

It is the writer's view that "fossil pressures," to use the picturesque expression of Mr. Pack, are to be considered as the rule in Nature and not the exception. The earth's body is in a constant state of readjustment, as well shown by seismic and kindred phenomena; and these phenomena draw their source from the past much more than from the present, as they point to the relief of slowly accumulated strains. When the lower sediments of a syncline are compressed by superincumbent strata, the first compression dates from the time of the first deposition of these strata; the "heaving" in mines, the deformation of rocks in quarries during operations, the production of fissures on the summit of arches denuded by erosion, etc., show as many traces of fossil strains. Would it be wise to deny the possibility of a fossil pressure where conditions for its formation and preservation seem to have been the best? If there has ever been such a thing as deformation through diastrophism, strains have been the result; and the gases inclosed in the strata, as well as the liquids in relation with them, having been submitted to these strains, must have acted as accumulators where favorable conditions obtained. They must show traces of these strains today, unless these traces have been dissipated since. But if they had been dissipated, would not the pressure due to gas formation have been dissipated in the same way? Further, the building up of rock pressure within the reservoir by the change of some oil into gas, seems to meet with a serious objection. Washburne has pointed out that crude oil is exothermic, and therefore has no tendency to split or decompose under its temperature of dissociation[19] ("Cracking point," from 250° to 400° C. and above); and the possibility of such a temperature could not be considered, as a rule. Thus, if oil migration is due primarily to rock deformation, it becomes difficult to escape the conclusion that rock pressure in an oil or gas pool is, at least partially, due to deformation itself.

The writer thinks that he has answered the different objections raised by his critics and shown that the items criticized agree with the diastrophic theory instead of being in opposition to it. But he does not intend to say that the theory cannot be amended or perfected. If the principles on which the theory is founded should be recognized as true, some definite and more complete form may be reached as a result of "team work," in which critics and criticisms may play their part.

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[19] *Trans.*, vol. 51, p. 607 (1915).