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THE GEOLOGIC RÔLE OF DILATANCY

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ABSTRACT

Dilatancy, the expansion of granular masses when deformed due to the rearrangement of the grains, was described and illustrated with many interesting experiments by Osborn Reynolds, an English physicist. In this paper the term is used in a broader sense to include all volume increase due to deformation. The consequences of dilatancy by deformation have far-reaching geologic significance. It is suggested that dilatancy is important in inducing faulting and jointing in unconsolidated sediments, in the movement of fluids—oil, water, and gas—contained in rocks, in initiating magmas and in certain of the processes accompanying intrusion and crystallization of magmas. The factors controlling the manner of deformation of unconsolidated granular masses are applied by analogy to a consideration of the manner of deformation of solid rocks by fracture and by rock flowage.

Dilatancy. The property of granular masses of expanding in bulk with change of shape. It is due to the increase of space between the individually rigid particles as they change their relative positions.—*Century Dictionary.*

This property of granular aggregates was described by Osborn Reynolds,[1] whose interest was apparently confined to its application in his mechanistic conception of the ether as applied to the development of a theory of gravitation. Dilatancy is a property of many earth materials, and is fundamentally related to the manner of response of these materials to deformation. It is the purpose of this paper to indicate the possible rôle of dilatancy in certain geologic processes. The term will be used in a somewhat broader sense, to include all volume increases due to deformation.

DILATANCY IN DEFORMATION OF INCOHERENT GRANULAR MASSES

Hard, spherical grains, such as shot, shaken down in a container, tend to arrange in a condition of maximum-density packing. If the grains are spherical and of uniform size, each grain is in contact with twelve neighboring grains. This arrangement has a minimum of voids, 25.9 per cent. It is obviously impossible to change the shape without increasing the volume of this aggregate (assuming that the

[1] Osborn Reynolds, *Scientific Papers*, Vol. II (1901), p. 217.

grains are not deformed), as any differential movement between the grains involves a change in the system of packing, which of necessity requires increase of voids and consequently of volume. This is illustrated in Figure 1, by a cross-section of spherical grains in close packing at the left, and the increase in volume occasioned by deformation of this mass at the right.

A mass made up of spherical grains of uniform size serves best for illustrative purposes. The property of dilatancy, however, is not

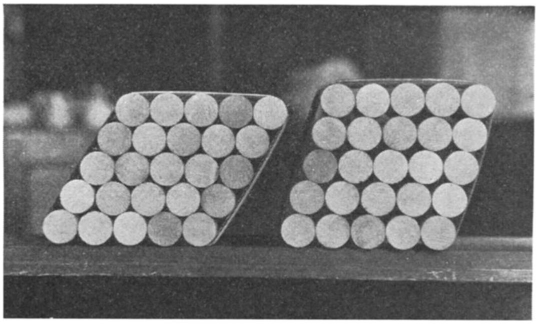


FIG. 1.—Illustrating the increase in voids and consequent increase in volume resulting from deformation of a mass of close-packed spherical grains. Cylinders of wood held by rubber bands and strips of cardboard serve to represent spherical grains in cross-section. This serves as a two-dimensional representation of dilatancy.

confined to masses of spherical grains, but is common to all granular aggregates, regardless of angularity of grains or degree of assortment.[1]

Quoting Reynolds, "The most striking evidence of dilatancy is obtained from the fact that since dilatant material cannot change its shape without increasing in volume, by preventing change of volume all change of shape is prevented."[2] This fact is beautifully illustrated by one of Reynolds' experiments. A toy rubber balloon, filled with sand and containing just sufficient water to saturate the

[1] When particles are so small that the adsorbed liquid or gaseous layers on their surfaces are thick in proportion to their radii, movement between the particles apparently takes place through deformation of the envelopes. This is illustrated by the behavior of aerated, fine dry powders, which simulate fluid in their behavior, and by damp, fine-grained clay.

[2] Osborn Reynolds, *Nature*, Vol. XXXIII, p. 30.

sand after it has been shaken down into a condition of dense packing, resists deformation to an astonishing degree, because sand so contained, when deformed, must increase in volume, and requires more water than is available to fill the increased proportion of voids. The result is that the fluid pressure within the container is greatly reduced and atmospheric pressure forces the rubber very tightly about the mass of sand, preventing dilation, increasing intergranular friction, and thereby inducing rigidity. The tensile strength of the water may also be a factor in the rigidity of the mass. When deformed (although Reynolds, not being interested in this phase of the experiment, makes no mention of it) it fails along definite shear planes, rather than by plastic yielding of the entire mass.

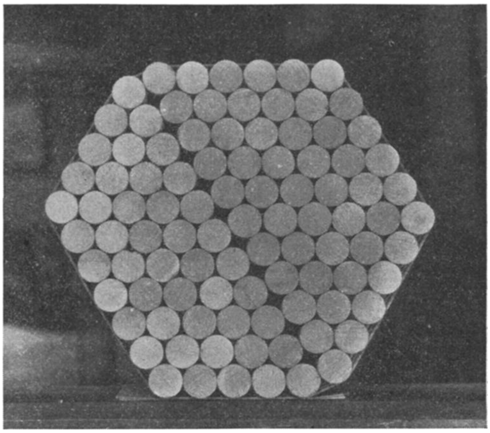


FIG. 2.—Wooden cylinders in triangular packing are held together by several very strong rubber bands. Increase in area is restricted by the containing pressure of the bands. One-sided pressure results in failure by shear with increase in area as shown. If increase in area is not prevented, the "grains" are all free to move relative to one another and single fractures as shown above do not develop.

The same phenomenon can be illustrated by a modification of Reynolds' experiment. If a rubber container, such as a toy balloon, is filled with sand and the air is pumped out, atmospheric pressure forces the rubber tightly against the contained sand, and the mass becomes exceedingly rigid. An 8-inch rubber balloon filled with dry sand and exhausted by an ordinary laboratory aspirator becomes as rigid as a solid rock, and gives out a musical tone, as does a stoneware jar, when struck with the knuckles. Rigidity is due to the containing pressures, but probably also to removal of air cushions from between the grains, both factors increasing intergranular friction. This evacuated, sand-filled, rubber sack behaves as a brittle solid, which fails by shear when deformed under pressure. A thin-walled cylinder filled with sand (with a small proportion of flowers of sulphur to serve as a binder), closed at both ends, and evacuated, fails along a definite shear plane under longitudinal pressure. By heating the deformed cylinder to the melting-point of sulphur, the mass of sand is solidified. Such a mass is illustrated with the container removed in Figure 3. Granular masses free to dilate deform by flow; when dilation is prevented or restricted, deformation causes fracture. Sand, either wet or dry, under relatively slight containing pressures, behaves essentially as a solid (as dilation is restricted) and, when deformed, fails largely by fracture along shear planes. This manner of failure requires a minimum increase in volume and involves dilation only in the shear zone. Plastic deformation of close-packed grains involves the entire mass deformed, and causes a much greater volume increase than that required by failure along definite shear planes.

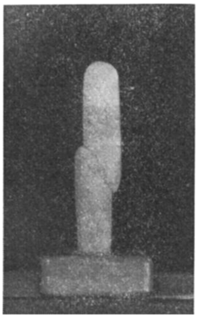


FIG. 3.—Failure by shear of dry sand held in a cylindrical rubber container and made rigid by pumping out the air. The mass was deformed by longitudinal compression.

The mechanical properties of fine, dry sand under no other containing pressures than its own weight are interesting in connection with the phenomena of dilatancy, and afford a means of simple experiments quite instructive in connection with problems of the mechanics of rock deformation. If sand, fine enough to pass through an 80-mesh screen, is poured out on two overlapping sheets of paper so that the pile of sand is partly on one sheet and

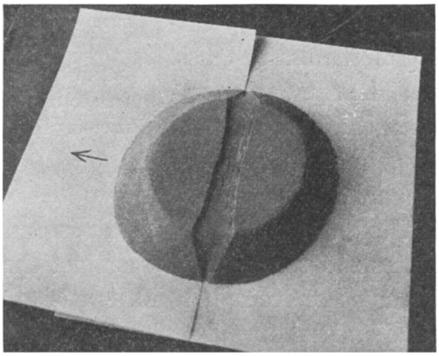


FIG. 4.—Graben fault in fine, dry sand, developed by moving the upper sheet of paper in the direction of the arrow.

partly on the other, and is leveled off to a thickness of approximately 2 cm., a graben fault may be produced by pulling the upper sheet of paper away from the lower in a direction at right angles to its covered edge. See Figure 4. If, with the sand again prepared as above described, the upper sheet of paper is moved *toward* its covered edge, a wedge of sand will be faulted upward in a horst. See Figure 5. If the upper sheet of paper is rotated about a point at its edge beneath the sand, a combination of graben and horst is produced. See Figure 6. If the sand is leveled out, as previously described, in a layer 2 cm. thick, and a small block is thrust slowly into the mass by sliding it along the paper, the sand displaced in front of the block will rise and override the undisturbed sand in a series of overthrust faults,[1] resembling in a rather striking way the well-known structure of the Scottish Highlands. In this case the easiest relief is upward, and movement is accomplished by faulting in this direction. If the sand is piled into a rather long, narrow ridge, as in Figure 8, and the block is thrust longitudinally into the ridge of sand, the direction of easiest relief is lateral, and the sand faults along nearly vertical planes at an angle to the direction of the movement.

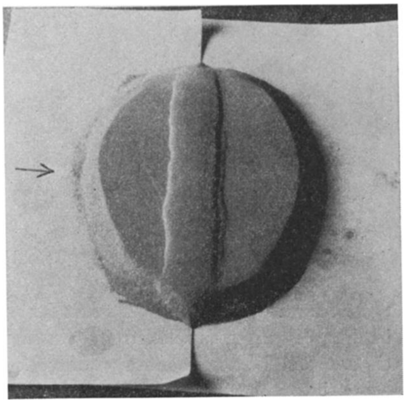


FIG. 5.—Faults producing a horst in fine, dry sand, developed by moving the upper sheet of paper in the direction of the arrow.

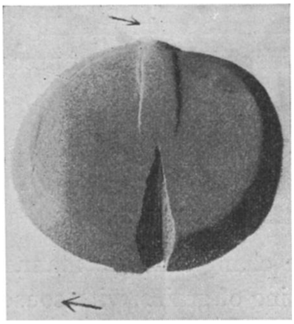
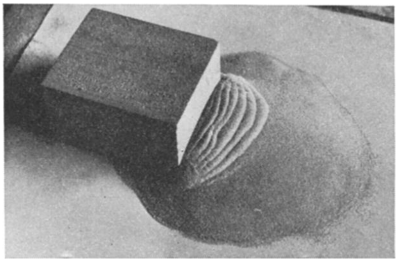


FIG. 6.—Combination of graben and horst produced by a rotational movement of one of the overlapping sheets of paper, as indicated by the arrows.

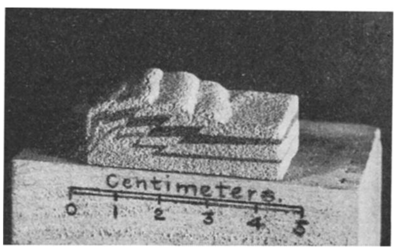
[1] R. T. Chamberlin and F. P. Shepard have described repeated overthrust faults in unconsolidated sand (*Journal of Geology*, Vol. XXXI [1923], pp. 511–12). Faults in

The geologic significance of the previously described properties of sand and allied granular aggregates is that even under very moderate load they tend to fail by fracture rather than by plastic flow, and that joints and faults in unconsolidated sediments are to be expected. The faulting and jointing in fine-grained glacial material so commonly observed (and so frequently marveled at) exemplify this property of granular aggregates. It seems probable that at least part of the jointing in sandstones and other sedimentary rocks may have had its origin in the deformation of these rocks prior to consolidation. The "grain" (a capacity to split along parallel surfaces across the stratification), so common in sandstones, may be the result of more open packing of the grains along planes of precementation dilatation.



a

FIG. 7*a*.—Repeated overthrust faults in fine, dry sand, developed by shoving the wooden box horizontally along the paper into the flat mass of sand. The direction of easiest relief is upward.



b

FIG. 7*b*.—Cross-section of faulted mass developed as shown in Figure 7*a*. Stratification is produced by sifting alternate layers of sand of different colors. The sand is cemented after deformation by heating the mass to a temperature sufficient to melt a small proportion of sulphur which had been incorporated in the mass.

EFFECT OF DILATANCY ON THE MOVEMENT OF FLUIDS CONTAINED IN SEDIMENTS

The changes in the manner of packing of grains, with consequent changes in voids, involves a movement of any fluids which may be contained in the voids.

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unconsolidated sand and clay were produced by thrusting a pressure block horizontally into the mass. The nature of the faulting was tested by means of straws stuck into the sand and by the action of the moving sand on smoked glass plates inserted in the mass at right angles to the pressure block.

An experiment illustrating this may be made by filling a thin-walled rubber cylinder (a section of automobile tire tubing) with sand, tightly closing the ends with large corks, and filling the voids in the sand with water to the point of complete saturation. If a glass tube is inserted through a hole in one of the corks and bent at right angles to a vertical position and partly filled with colored water it serves as an indicator of the change in volume of the sand. It is found that this sand-filled cylinder cannot be bent or squeezed or deformed in any manner without lowering the level of the water in the vertical tube. This suggests that there must be a movement of contained fluids in sediments toward regions of deformation, as these are regions of dilatation, due to both rearrangement of grains and to rock fracture. It is believed that this phenomenon should not be neglected as one of the processes controlling the movement of oil, water, and gas, and as one of the reasons for the movement of oil toward anticlines and monoclines.

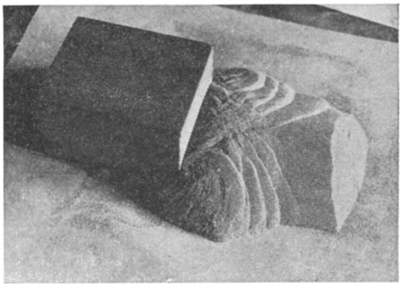

FIG. 8.—The sand was piled in a narrow ridge and the box thrust longitudinally into the mass. The direction of easiest relief is lateral and the sand faults along nearly vertical planes inclined to the direction of the movement.

It has been shown that if the amount of fluid in the granular aggregate is only sufficient to fill the voids in the condition of maximum-density packing, the mass fails largely by fracture, and not by plastic deformation. If fluid is available slightly in excess of this amount, the aggregate is easily deformed plastically up to the point where the increased voids absorb the available fluid. At this point the mass becomes rigid. This is well illustrated by a toy balloon filled with sand and water, with the latter somewhat in excess of the amount required to saturate the sand in a condition of dense packing. The balloon so filled is soft and easily deformed *up to a certain point.* If squeezed in the hand, it suddenly becomes rigid when the volume of voids and the volume of water become equal. If more water is added, a condition is reached where the balloon is soft and easily deformed to any extent without becoming rigid. There is enough water present to fill the voids when the sand is in the most open arrangement possible. In this condition deformation does not involve an increase in volume of the balloon, and the mass changes its shape by plastic flow and offers very little resistance to deformation. This state of affairs is illustrated in nature by quicksand, which contains sufficient water to permit the most open arrangement of the grains—usually found in a situation where an upward current of water keeps the sand in open packing. Quicksand becomes very firm when this excess of water is drained away.

The mechanics of certain types of landslides, of mud flows, of failure of earth dams, involve in a large measure the factors of dilatancy. A comparatively small change in the water content of a mass of earth or sand changes it from a stable, comparatively rigid condition to a relatively fluid condition. Initial movement of the mass is an important factor, as it causes dilatation, which increases the voids, draws in water, and causes the mass, on passing the critical point, to move as a fluid.

DILATANCY IN THE DEFORMATION OF SOLID ROCKS

It is convenient to refer to the hard grains as the solid phase and to the material between the grains as the fluid phase. Using these terms, then, the experimental work seems to demonstrate two general principles. (1) When the fluid phase is sufficient only to fill the voids with the grains in a condition of maximum-density packing, deformation of the mass requires increase in volume. (2) When the available fluid phase is sufficient to fill the voids with the grains arranged in minimum-density packing, the mass may be deformed to any extent without increase in volume.

The writer believes that this conception can safely and profitably be carried over to a consideration of the mechanics of deformation of the solid rocks. Rocks in general may be regarded as granular aggregates. To the extent that they are porous, the pores represent the volume of a fluid phase, but the amount of fluid phase is, with the exception of a few special cases, too small to play much part in determining the manner of deformation. A sandstone, if cemented sufficiently to merit the term, has less porosity than sand. The small proportion of a fluid phase causes all solid rocks at or near the surface to yield to deformation by fracture, with increase in volume. This fracturing of rocks clearly involves dilatation, and the net volume of the fractured mass has been increased by the total volume of the openings produced.

That the deformation of brittle materials involves an increase in volume *prior* to their failure has been generally recognized. Bucher[1] has discussed this matter in a consideration of the mechanical interpretation of joints, and quotes Chwolson, who gives a formula connecting the modulus of volume increase with Young's modulus and Poisson's ratio. He also quotes the work of Kahlbaum and Seidler, and of Lea and Thomas, as giving experimental evidence for increase in volume accompanying deformation under one-sided compression. That this increase in volume occasioned by deformative stresses imparts a greatly increased rigidity to the rock when under great containing pressures appears very probable. Bucher offers no explanation of how this increase in volume is accomplished, whether by change in the physical nature of the material itself, or by the development of voids.

When rocks are deformed under certain conditions involving high confining pressures and a proper rate of application of deforming stresses, they yield to deformation by plastic flow with the development of schistose textures characteristic of rock flowage. This manner of yielding to deformation does not involve a general fracturing of the rock, and probably does not require increase in volume. If the analogy of the requirements for plastic deformation of an unconsolidated granular mass be carried over to the case of rock flowage of a solid rock, it is necessary to conceive of the latter as consisting of a solid phase of hard grains and of a fluid phase surrounding these grains of a sufficient amount to permit the movement of the hard grains without occasioning dilatation of the mass by their interference. The solid phase is represented by the harder, more resistant minerals. The fluid phase is represented by those constituents of the rock which are relatively mobile, as evidenced by their rearrangement to schistose structures through processes of crystallization and recrystallization. This involves a complete atomic or molecular rearrangement of that portion of the rock.

[1] Walter H. Bucher, *Journal of Geology*, Vol. XXIX, p. 1.

Solid rocks in general, then, may be considered as granular aggregates consisting of a solid phase and a *potentially* fluid phase, which is caused to function as a fluid phase under certain conditions of composition, pressure, temperature, and rate of deformation. To make this clear let us revert for the time being to a modification of the simple concept of a granular mass consisting of sand and water. In this case a mass of sand, well shaken down into close packing with the voids filled with asphaltum instead of water, is used. The sand grains constitute a solid phase, the asphaltum a potentially fluid phase. A block of this asphalt-cemented, closely packed sand cannot fail except by fracture, even if deformation is applied very slowly, because the amount of fluid phase is not sufficient to permit plastic deformation. If, however, a mixture of sand and asphaltum be taken, with sufficient asphaltum to permit freedom among the sand grains equivalent to that in cubic or minimum-density packing, the resulting aggregate is such that under slow deformation at ordinary temperatures, or under more rapid deformation at higher temperatures (under which the asphaltum would soften), it would yield by plastic deformation of the entire mass without increase in volume. The asphaltum, or potentially fluid phase, would function as a fluid. If, on the other hand, the aggregate is deformed rapidly, the asphalt would not be able to function as a fluid, and the mass would fail by fracture, with an increase in volume.

This analogy of the asphaltum-sand aggregate may be applied to the flowage or fracture of rocks. Under conditions of rock flowage that portion of the rock which undergoes molecular or atomic rearrangement constitutes the fluid phase. If the rate of deformation under the existing conditions of temperature and pressure is too great to permit this rearrangement, the rock fails by fracture; and if the rate of deformation is slow enough to permit this rearrangement, failure is by plastic flow, provided the solid phase is sufficiently dispersed to prevent dilatation. If the amount of the fluid phase is intermediate, the deformation will be by combination of plastic flow and fracture, the grains of the solid phase being fractured and granulated through their mutual interference, the factures being filled by movement of the fluid phase into the openings; the net volume change is determined by the degree to which the increase of volume due to fracturing of the solid grains is balanced by the decrease in volume due to development of new compounds of higher density in the fluid phase.

The zones of schist so commonly found marking planes of movement in massive igneous rocks differ in composition from the massive rock by having more combined water and less lime and soda. Mineralogically they are characterized by an increased amount of platey minerals, micas, and chlorite. That these schists may have been developed along zones previously weathered or hydrothermally altered is a possible explanation for the change in chemical composition. It is equally probable that the increase in water and loss of other constituents has in some instances been contemporaneous with the deformation of the rock along this zone. Because the development of a schist from a strong massive rock presupposes deep burial with intense rock pressures and deformative stresses of great magnitude, it has been difficult to reconcile the introduction of water, and the escape of constituents known to be lost, with the condition of great pressure, which on first thought would appear to tend toward the squeezing out of any water present and the prevention of any ingress of fluids. If it be assumed that deformation has been too rapid to permit the potentially fluid phase of the rock to function, there has been increase in volume as a result of deformation within the elastic limit, and as a result of crushing and fracturing. This dilated zone is a region of low *fluid* pressures, and any available fluids will move to fill these openings. Under the conditions of temperature and pressure they will have highly reactive and solvent properties, and metamorphic changes with the development of hydrous minerals would ensue. Continued and perhaps slower movement along this zone of yielding finds a rock partly adapted by composition to rock flowage, and any excess water, with a high content of dissolved mineral matter, is squeezed out.

It is interesting to speculate on the possible relationship of dilatancy to the manner of deformation of rocks at depth. The fact that yielding by fracture involves increase in volume, while rock flowage does not, suggests that the increased prominence of flowage with increase in depth is due to the fact that flowage does not require the lifting of the equivalent of the gravitational load, and therefore may not require stress differentials as great as would be demanded for rock fracture.

DILATANCY AND ORIGIN OF MAGMAS

If the conclusion be accepted that deformation of a rock by flowage requires that the rate of deformation be slow enough to permit the potentially fluid phase of the rock to function as a fluid, and that deformation at a more rapid rate must of necessity produce failure by fracture, it follows that great and comparatively rapid deformations of the earth's crust may extend far below the surface and well into the zone normally characterized by rock flowage. If this is at a depth where the rocks are at a temperature above their melting-point but are kept solid by pressure, the result of fracture-dilatation would be immediate liquifaction of the rock in that zone to an extent measured by the increase in volume. This fluid rock migrating by way of the fracture zone to regions of lower pressure would remain fluid and contain sufficient excess heat to fuse a certain amount of rock in its path. The presence and movement of this fluid material would considerably upset the dynamic stability of the whole, and result in the development of magma and magmatic activities of greater or lesser extent, depending on the magnitude of the original deformation.

DILATANCY IN MAGMATIC PROCESSES

An igneous magma in the process of solidification can be considered as a granular mass made up of a solid phase (the mineral crystals) and a fluid phase. The mass has the properties of a fluid until solidification has proceeded to a point where the solid phase is so abundant that the grains are no longer free to move, but interfere with one another when the mass is deformed. In this condition the mass can no longer behave as a fluid, and is incapable of being injected into openings in the surrounding rock due to the great rigidity imparted to it by deformative stresses. It follows from this that plastic flow of igneous rock must occur before cooling has developed the solid phase sufficiently to make the mass potentially dilatant. After this potentially dilatant condition of the magma has been reached, it seems reasonable to suppose that any openings or fissures in the surrounding rock will be filled, not by movement of the magma as a whole, but by the flowing out of its fluid phase under the fluid pressure of the liquid magma from the interior of the mass. This fluid phase would differ in composition from the solid phase, and consequently from the magma as a whole, by being in general more acid and containing a larger amount of mineralizers, in short, pegmatitic or aplitic in nature.

The potentially dilatant mass itself would also be capable of fracture under rapid deformation, and these fractures would be filled likewise by the fluid phase, resulting in thin dike-like occurrences of pegmatitic or aplitic material having vaguely defined, blending boundaries of the type so commonly observed in igneous masses.

Zones of deformation not resulting in fracture of the partly solidified magma would conceivably produce zones of more open packing of the solid grains, resulting in a greater proportion of the fluid phase and a consequent difference in composition of these zones of movement. If these zones of deformation or shear were closely spaced and parallel, as is quite reasonable, it is conceivable that the result would be a banding of the rock in the manner of certain of the primary gneisses.

Protoclastic structure may be developed by the interference of the solid particles during deformation of a potentially dilatant magma.

The movement of the fluid phase from the hotter portions of the magma would result in a reheating of the zone into which the hotter fluid magma migrated, with consequent interruption in the normal growth of a solid phase, cause re-solution, and the development of zonal growths of changed composition.

SUMMARY

Incoherent, granular masses, such as sand, in a condition approaching maximum-density packing, are dilated by deformation. In a condition of open packing they deform without dilatation. Prevention of free dilatation by enclosing pressures induces failure by fracture or shear when the mass is deformed, and with the development of joints and faults along thin zones of dilatation.

Deformation of a potentially dilatant mass causes *decrease* in pressure of the fluid portion, and therefore fluids in rocks—water, oil, gas—move toward regions of dilatation.

The mechanics of response to deformation of incoherent granular masses is applied by analogy to solid rocks by conceiving of them as having a solid and a *potentially* fluid phase. When the latter functions as a fluid, the rock yields to deformation by flowing, otherwise by fracture.

Dilatation occasioned by deeply penetrating zones of fracture initiates magmas. Cooling magmas become potentially dilatant when the solid phase develops beyond a certain proportion. The fluid phase alone is then mobile and forms dikes and veins in the surrounding rock and in the granular mass itself. The flow of the fluid phase into cooler parts causes reheating of those parts.