THE

AMERICAN JOURNAL OF SCIENCE

[FOURTH SERIES.]

ART. XI.—*The Mechanics of Igneous Intrusion.* (Second Paper); by REGINALD A. DALY.

(By permission of the Director of the Geological Survey of Canada.)

CONTENTS:

Introduction.—In a recent number of this Journal* the writer has presented some of the facts upon which has been based a hypothesis on the development of the larger magma-chambers now occupied by plutonic rocks. There was entailed in the working out of that hypothesis a brief treatment of a necessary corollary—abyssal assimilation of the formation invaded by stock or batholith. The hypothesis was stated in general terms, without a full discussion of some of the fundamental postulates and conclusions and without detailed reference to individual areas. In Bulletin 209 of the United States Geological Survey the application of the hypothesis to a rather complex group of stocks occurring in and about Mt. Ascutney, Vermont, has been made, and some degree of assurance attained that this view of intrusion is there of greater value in explanation than are the older theories of intrusion mechanism.

* This Journal, vol. xv, p. 269, April, 1903.

In the present communication certain other concrete illustrations will be offered along with additional discussion of some of the main premises on which the newer hypothesis is based. Among these premises are: (1) the generally high fluidity of igneous magmas during the time of active intrusion; (2) the normally extensive shattering of the invaded formations at their contacts with plutonic magmas; and (3) the reality of "overhead stoping" of the blocks so shattered and rifted off from wall or roof of the chamber. Concerning the first and last of these premises certain difficulties were hinted at or partially discussed in the former paper, but their importance demands that further attention be paid to them. A note on a particular point referring to the first-mentioned premise may well anticipate the larger division of this paper, which will have to do primarily with contact-shattering in general and with the testimony of several Canadian intrusive bodies as to the validity of the rifting and stoping hypothesis.

The origin and suspension of basic segregations: bearing on the doctrine of the liquidity of plutonic magmas.—At first sight, the common occurrence of basic segregations freely suspended in their rock-matrix always less dense than themselves seems in one way to militate against the idea of high fluidity in igneous magmas. It is true that the mere fact of that particular kind of differentiation calls for the assumption of no inconsiderable degree of mobility in the igneous mass; but the question arises as to how that substance now represented by heavy minerals could be segregated and held up in a less dense matrix possessing such liquidity. That segregations have been so suspended seems clear in the average field occurrence. The question raises a second one as to the relative densities of molten segregation and molten matrix. If it can be shown that in the *fluid* state, matrix and segregation are nearly of the same density, the difficulty disappears and therewith the objection to the theory of high liquidity.

While the variations in thermal expansion of the common plutonic rocks are confined to narrow limits, the experiments so far made on the volumetric increase observed in the passage of single crystalline minerals to the glassy condition (at room temperature) appear to show that the law of even approximately constant ratio of expansion in rock-forming minerals does not hold. The following table taken from Zirkel's Lehrbuch der Petrographie (1893, vol. i, p. 681) synopsizes the results of Deville, Thoulet and others. The percentage decrease in density suffered by the minerals investigated when these pass from the crystalline state to that of cold glass is as follows:

Quartz	16·85 %
Olivine	16·30
Augite	14·18
Hornblende	12·13
Oligoclase	12·19
Orthoclase	10·21
Microcline	9·15
Adular	7·96
Sanidine	7·63
Labradorite	6·28

Barus has shown that, for silicates, the solidification contraction decreases in proportion as the thermal expansion decreases.* Since the thermal expansion is in direct proportion to the decrease of density affecting a crystalline silicate passing to the cold glassy state, it follows that the percentages of the table are in nearly constant ratio to the percentage decreases of density affecting the respective glasses when fused to a thoroughly molten condition. According to Barus, diabase loses 10 per cent in density in passing from rock at 20° C. to glass at 20° C. and its glass loses 7·2 per cent in density in passing from 20° C. to 1400° C., at which temperature it is very fluid. It is highly probable, therefore, that olivine glass would lose in density something like $7{\cdot}2 \times \frac{16{\cdot}3}{10{\cdot}0} = 11{\cdot}7$ per cent in assuming the same temperature of 1400° C. The net result on that assumption would be to give Fogo olivine, for example (spec. grav., 3·381) a specific gravity of about 2·50 at 1400° C. The specific gravity of gabbro at 20° C. becomes, when molten at 1400° C., changed to the following values:†

Spec. grav. at 20° C. Holocrystalline gabbro.	Spec. grav. at 1400° C. Molten glass.
2·90	2·42
3·00	2·51
3·10	2·59

Assuming the approximate correctness of these figures, it is possible to credit the flotation of molten globules of the olivine substance in a highly fluid gabbro or basalt. The rock-matrix would crystallize before the segregation or, at least, would have attained an antecedent viscosity great enough to support the more dense, because crystallizing, olivine. The foregoing reasoning leads to the suggestion for actual experimentation with olivine similar to that so successfully carried out for diabase by Barus. Without such fusion tests it is not

* Bull. U. S. Geol. Surv., No. 103, p. 43, 1893.
† This Journal, April, 1903, p. 277.

possible to tread on sure theoretical ground in dealing with the origin of olivine nodules in basalt, much less in accounting for the more important basic segregations of granites, syenites, etc. It is noteworthy that, besides olivine, augite, hornblende and oligoclase appear to have unusually high coefficients of cubical expansion, and that these minerals are among the commoner constituents of segregations in granites and syenites. The highly important constituent, biotite, has not been, perhaps cannot be, directly investigated in this regard. In the absence of experimental data, the further discussion of basic nodules in the present connection cannot afford very fruitful conclusions. All that seems certain is that the existence of basic segregations does not disprove a high degree of fluidity for plutonic magmas.

Shattering at plutonic contacts.

Among the commonest phenomena associated with the contact-zones of plutonic, igneous rock-bodies (bosses, stocks and batholiths) is that of extensive shattering and disruption of the invaded formations along the contacts. A host of memoirs on exotic granite, syenite, diorite, gabbro and other deep-seated rock-masses contain references to this particular phenomenon. It consists, in its ideal development, of the appearance of two concentric zones of mixed rock occurring between the homogenous main body of igneous material and the encircling country-rock unaffected by any serious mechanical disturbance due to the intrusion. Both zones lie parallel to the average line of contact between the intrusive and the country-rock.

The Zone of Apophyses.—The belt more remote from the intrusive body is generally much the broader of the two and consists of country-rock intersected by more or less numerous apophyses from the main igneous mass. These dikes and sheets are often seen to radiate outward in directions roughly normal to the average line of contact; but others running at all angles to the contact are usually associated. The whole group of apophyses has often thus a reticulate ground-plan and a reticulate vertical section. The portions of the invaded formation bounded by the apophyses are not essentially disturbed from the relative positions they occupied before the intrusion took place. This belt may be called "the zone of apophyses." According to the prevailing views among geologists, the zone owes its origin to a mechanical process of relative simplicity, namely, the injection of the molten magma forced by great pressure into all accessible planes of weakness within the invaded formation. The force may be hydrostatic, due to the weight of the chamber-roof or of part of that roof; or, among other causes, the energy may be derived from the necessary expansion of volume suffered by the digestion of solid country-rock by the magma.* The development of the fissures now filled with apophysal material may, however, be powerfully aided by a third cause that controls as well the formation of the other of the two zones noted above. It may be believed that a common disrupting force has affected both zones; a brief description of the second zone may anticipate the analysis of the conditions which demand the energetic working of that force.

The Zone of Inclusions; its origin.—The second zone is composed of igneous rock enclosing blocks of the country-rock. As the apophyses, breaking the continuity of the invaded formation, vary enormously in number within the outer zone, so the blocks, breaking the continuity of the igneous body, show the greatest variation in the degree of their abundance. This "zone of inclusions" varies in width from a few meters to three kilometers or more. The blocks, unless very close together and possessing thoroughly massive structure themselves, usually show clear evidence of having been shifted out of their former relative positions in the invaded formation, so that their original orientation is completely lost. There are transitions to the outer zone through the gradual increase in the number of blocks left undisturbed from their original orientation; and there is, of course, no easily fixed boundary between the zone of inclusions and the main intrusive body in which country-rock inclusions are normally absent or very rare. The inner boundary of the zone of inclusions is often difficult to determine in the case of stock or batholith so exposed to view by denudation as to furnish a land-surface close to the former roof of the magma-chamber.

Whatever be the causes of the disruption of blocks now found in the zone of inclusions, those causes are directly connected with the intrusive body itself and are thus not external. The zone is, for example, not due in the normal case to the injection of magma into rock coarsely brecciated by regional dynamic movements in the earth's crust. Movements of that sort tend generally to brecciate rock along straight or open-curve lines and would not necessarily follow the complex, sinuous, closed-curve line of contact such as belongs to a plutonic body. There is certainly, on the other hand, a genetic relation between the zone of inclusions and the replacement of the country-rock by great bodies of intruded magma almost or quite free of foreign fragments. Many authors speak of the inclusions as having been "torn off" or "carried up" by the

* This Journal, April, 1903, p. 289.

ascending magma, without, however, showing the possibility of such a process when correlated with the apparently demonstrated fact of the high liquidity of plutonic magmas. On the assumption of high liquidity at the moment of the immersion of the blocks, they would, in the average case, not remain near the molar contact,* but would sink into the depths of the magma-chamber. It is further impossible to believe that any kind of current action in the magma could carry on a sort of erosion on the chamber-walls, a hypothesis which likewise would fail to explain the constant relation of the zone of inclusions to the molar contact.

Some of the blocks within the zone of inclusions have unquestionably been floated out or sunk from the molar contact after those portions of the country-rock have been completely surrounded by magma of the main body and of anastomosing apophyses. But there are reasons for concluding that apophyses of an abundance, matching the countless inclusions of many internal contact-belts, were not formed simply by reason of hydrostatic pressure forcing magma into original cracks or fissures in the country-rock. The conditions reigning at the contact imply the exhibition of a different source of energy—one which many geologists have incidentally credited with the shattering effect. A clear, positive statement of the case has been given by Crosby in his monograph on the Blue Hills Complex.† The subject is of importance and merits much more discussion than can be brought into the few pages of this paper; it is, moreover, a difficult subject, largely on account of the existing lack of experimental data, and the following treatment of it can lay claim to doing little more than open up the problem and make the attack upon it in a qualitative manner.

Shattering by differential thermal expansion in the invaded formation.—It is manifestly impossible to determine the exact rise of temperature which will occur in a formation at the contact with an invading magma. Both elements, the pre-eruption temperature of the country-rock and the temperature of the magma itself, are partly indeterminate. If the former be regulated by the normal law of the vertical distribution of the isogeotherms, that temperature will be about 200° C at a depth of four miles below the earth's surface—possibly a rather liberally estimated average depth for the upper limit of a granitic magma-chamber. If we assume that the temperature of an intruding magma is approximately that at which the rock resulting from its crystallization becomes thinly molten under plutonic pressures (an assumption apparently justifiable from

* The main contact, that of igneous body *mass* against country-rock *mass*, as distinguished from the minor contact of inclusion and intrusive rock.

† Occasional Papers, Boston Soc. Nat. Hist., iv, 1900, p. 315.

the known properties of lavas and notwithstanding the presence of mineralizing agents), there should occur by conduction *at* the molar contact, a rise of temperature in the invaded formation, of something like 1000° C. That would mean a cubic expansion in the solid rock of between 2·5 per cent and 3·0 per cent, corresponding to a linear expansion of about 0·9 per cent.* The force required to prevent that degree of expansion is equal to the amount of pressure required to compress the rock by the same amount. The coefficient of compressibility for ordinary crystalline and well-cemented sedimentary rock is not far from that of glass, viz.: about 0·0000025 per atmosphere of pressure. Assuming that the thermal expansion should so occur that the volumetric change would be exactly in the reverse sense of the volumetric change observed during compression tests for solids, and assuming that the just mentioned coefficient of compressibility should apply at very high pressures, it follows that the inconceivable pressure of more than one million atmospheres, or about 8000 tons to the square inch, would be required to prevent the expansion of rock raised 1000° C. in temperature. However great the expansion transverse to the plane of the molar contact may be, a large proportion of the force of expansion must pass into the form of compressive strain, developing lines of force in the plane of the contact. If only one per cent of the total force of expansion were applied in that plane, the integrity of the rock must be destroyed, for the crushing strength of rock is in no case as much as fifteen tons to the square inch.

It is extremely difficult, if not impossible, to imagine the enormous and complicated stresses set up in this way. Although the heat of the intrusion would be conducted outwards in all directions from the igneous body, the supposition is reasonable that the temperature reigning only a few hundreds of meters from the intrusive would be very much lower than that at the contact. Differential expansion and consequent intense shearing stresses far above the breaking strain of rock-material might thus be produced. That action would be complicated and intensified by the variable values of heat-conduction in the invaded formation which is always more or less heterogeneous. The following table of relative values calculated from Everett's "Units and Physical Constants" (1879, pp. 101 and 103) shows the importance of differential conduction in different rocks. For ease of comparison all the other values are referred to the conductibility (taken as unity) of calcareous sandstone.

* This Journal, April, 1903, p. 274.

Rock.	Conductibility.
Calcareous sandstone	1·00
Clay slate	1·24
Slate, across cleavage	1·60
Trap	1·97
Micaceous flagstone, across cleavage	2·09
Limestones (mean)	2·44
Granites (mean)	2·51
Sandstones and hard grit (dry)	2·58
Sandstones and hard grit (wet)	2·80
Slate, along cleavage	2·84
Micaceous flagstone, along cleavage	3·00
Sandstone of Craigleith quarry	5·06

The table illustrates the well known fact that, in a rock-mass possessing the plane-parallel structure, the rate of conduction is widely different according as the heat passes along or across the planes of schistosity or cleavage. Such differential conduction and consequent differential expansion may be held responsible for the opening of fissures for the entrance of apophysal igneous matter in spite of the general tendency of the expansion to close preëxisting cavities in the country-rock. The apophyses themselves by virtue of their own high temperature must hasten the destructive action.

Part of the stress-energy set free might be added to that of injection and expended in the minute crumpling of relatively plastic bedded country-rock. Another portion is conceivably expended in irregular and perhaps very complete shattering of the rock, which by that action is relieved from the strains by sudden rending and fracturing rather than by any form of rock-flowage. Still a third portion of the energy might become potentialized as in Rupert's drops, Bologna glasses or certain slickensided rock surfaces,* and only finally expressed as a shatter-force after sudden faulting or other shock in the country-rock had precipitated the destruction, repeating on a large scale, the destruction of a Rupert's drop.

Exfoliation at plutonic molar contacts.—The complexity of these mighty interacting forces is such that the shattering produced by them cannot be referred to simple strain-categories. Experiments and certain observations made in rock-quarries seem to throw light on one of the more important and simpler methods by which disruption of the country-rock may take place. A short statement of the facts derived from each kind of study will serve to place the question of the efficiency of this process in a clearer light.

Reade has given so concise an account of his experiments on the differential expansion of stone that his descriptions of cer-

* A. A. Julien, Jour. Franklin Inst., cxlvii, 1899, p. 382.

tain typical trials may be given in full. "A bar of fine hard light brown sandstone, square-dressed to a smooth surface, measuring between two fixed points 7·346 inches long at 61° F., and roughly speaking 1¾ inch by 1 inch scantling, was placed with its ends resting flatways on two supports. The flame of the blowpipe was brought to bear upon the upper surface until it expanded to 7·385 inches. The stone was hot enough to melt solder but not lead—perhaps 500° F. on the top surface. As the blowpipe played upon the stone it became, in places immediately under the flame, momentarily heated on the surface to a bright red heat, and the sharp edges were burnt off; the stone became when cool of a darker brown, but apparently was not otherwise altered by heat. The stone arched upwards against gravity in a most remarkable manner to the extent of $\frac{1}{32}$ of an inch. A second heating brought it up to not less than $\frac{1}{16}$ inch, at which it took a permanent set."* Bars of Sicilian white marble and of oolitic marble, about 14·5 inches in length, were similarly arched $\frac{1}{16}$ inch and permanently distorted. A square slab of Sicilian marble 12 inches on the side and ¾ inch thick was placed upon two bars of slate. "It was heated with a blowpipe on the upper surface. The flame was rather small, and was kept mostly near the centre within the circle of dotted lines (shown in Reade's figure), but was also moved about. The slab became very slightly convex. Eventually it cracked. . . . . The crack was the result of the circumferential and radial expansion of the centre part of the slab, within the dotted lines, and shows that a considerable bursting strain was developed."†

The conditions of differential heating in these experiments are analogous to those found at intrusive contacts. The warping of the shell of country-rock immediately adjacent to the molar contact must be of a higher order than in the case of the stone slabs because of the fact that the shell is nowhere free to expand in the plane of the heated surface. The warping would not be interfered with by the pressure of the magma if the latter had access through opening fissures to the outer, cooler surface of the shell. Such fissures would be formed along original planes of fission roughly parallel to the contact, or along shearing planes produced in the same position by virtue of the differential expansion itself. With the intrusion of this apophysal material and the more thorough heating of the warped shell, expansion would be intensified, and, as has been seen, a force would be developed vastly greater than the strength of the rock could withstand. The bending or shearing shell must finally collapse and become shattered into separ-

* Origin of Mountain Ranges, London, 1886, p. 22.
† Ibid, p. 23.

ate masses of solid rock now wholly or partially immersed in the magma.

The process is thus one of exfoliation on a large scale. It is comparable to the rifting action of heat on masonry and on granitic masses "said to have been made a matter of quarry utility in India. It is stated (Nature, January 17, 1895) that a wood fire built upon the surface of the granite ledge and pushed slowly forward causes the stone to rift out in sheets six inches or so in thickness, and of almost any desired superficial area. Slabs 60x40 feet in area, varying not more than half an inch from a uniform thickness throughout, have been thus obtained. In one instance mentioned, the surface passed over by the line of fire was 460 feet, setting free an area of stone of 740 square feet of an average thickness of five inches."* Merrill gives a striking illustration of the exfoliation of granite consequent on thermal expansion and general weathering of the rock composing Stone Mt., Georgia.† Again, the observations made by Niles in connection with operations in several New England quarries corroborate the belief that the exfoliation at plutonic igneous contacts must be well qualified to shatter the invaded formations. At a gneiss quarry of Monson, Mass., the rock is under notable stress due to local crustal compression. A rough measure of the amount of that pressure is found in the sudden visible expansion affecting great slabs of the gneiss which, in the quarrying process, are freed from their beds. "In one mass of rock, 354 feet long, 11 feet wide and 3 feet thick, the amount of expansion after dislodgment was 1½ inches up the slope of the hill.' When the fracture by wedging is suddenly and thoroughly made, the expansion takes place immediately, and sometimes the expansive force itself completes the desired work, the stone suddenly springing into the elongated state. Spontaneous fractures also occur, of which one was fully 4 inches wide. On removal of overlying beds, spontaneous upward bendings and swellings of the lower beds also occur, most frequently in the thinner sheets, up to 4 feet in thickness, with formation of miniature anticlinals. The amount of elevation varies from ¼ inch to 3 or 4 inches, even in a single afternoon. The span of the arch thus formed is sometimes 50 feet, while some are only 3 feet broad; the crests always trend in easterly and westerly directions, are sometimes ruptured, and are evidently caused by expansive thrust in northerly and southerly directions, since the edge of the sheet at each base of the anticlinal arch remains so closely attached to the underlying bed that no lateral slipping of this edge of the rock could possibly have taken place."‡ Similar exfoliation and arching of limestone is reported by Niles from Lemont, Ill.

* G. P. Merrill, Rocks, Rock-weathering and Soils. p. 182, New York, 1897.
† Ibid, p. 245. ‡ Julien, op. cit., p. 386.

"In one quarry, also, there was an elevation of a part of the bed forming the floor. It was an anticlinal axis of more than 800 feet in length, and its trend was nearly east and west. In its most conspicuous part the elevation was from 6 to 8 inches, and the arch measured from 16 to 18 feet from base to base over the crest."*

Notwithstanding the spectacular nature of these sample phenomena observed in different quarries, the forces engaged in their production are almost insignificant compared with those which must be produced in the shell of country-rock concentric with the molar contact of a still molten stock or batholith. The latter forces may be compared with the force of compression which has so often developed peripheral cleavage and schistosity concentric with molar contacts of stocks and batholiths; but fracture is the necessary product of the one kind of energy applied suddenly, as rock-flowage is the product of the other applied slowly and for a much greater period of time.

Differential heating of the invaded formation will, then, through exfoliation and still more irregular shattering, cause the mechanical destruction of the chamber-vault. If the magma be thoroughly molten, the rock-fragments so immersed in it, will, by the balance of probabilities for the average case, sink in the magma. The new surface of the country-rock so exposed to the hot magma must undergo a similar process. The magma chamber may in this way be gradually enlarged so long as the magma preserves sufficient heat for the purpose. Near the time of final solidification the high viscosity must prevent the sinking of the blocks which are last isolated in the magma. The "zone of inclusions" and its organic relation to the molar contact actually to be observed in plutonic rock-bodies seem to find adequate explanation by this hypothesis.

Illustration from the Madoc-Marmora District of Ontario.

The best published example of a granite stock mapped with the distinct purpose of illustrating a shatter-zone is doubtless that due to the labors of Coste and White in the Madoc-Marmora Mining District of Ontario.† A reduced copy of the map is represented in fig. 1. The legend expresses practically all the information yet printed in connection with the region since the survey was made. Mr. Coste has kindly given the writer certain additional statements on this interesting group of granite bosses; the following quotations are taken from his letter dealing with the matter. "You are quite right in your

*Julien, op. cit., p. 391.

† Geol. and Nat. Hist. Surv. of Canada, Special sheet; ½ mile to 1 inch, published without text, 1886.

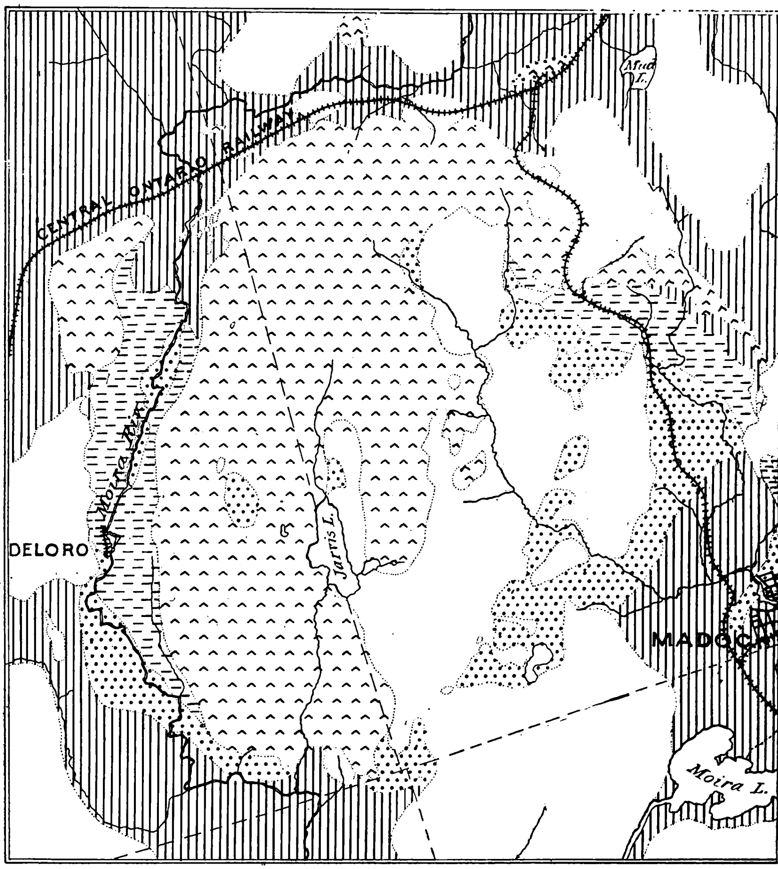

Fig. 1.

Bird's Eye and Black River Limestone ; Ordovician.

Intrusive granite.

("Gr. A.B.") Granite enclosing fragments of Archean—Zone of Inclusions.

("A.B. Gr.") Archean altered by the granitic intrusion and cut by many dikes—Zone of Apophyses.

Archean ; chiefly crystalline limestone and calc schists.

Scale: 1 : 126,720.

understanding of the Madoc and Marmora District as a fine example of contact-shattering by an eruptive. The zone on my map '$\frac{\text{A. B.}}{\text{Gr.}}$' is preëminently a zone of apophyses, these being very numerous, running in every direction, more numerous than elsewhere (except in the zone '$\frac{\text{Gr.}}{\text{A.B.}}$') and being mostly fine-grained granite with little or no mica . . . Both zones form decidedly a zone of strong shattering about the intrusive, extending, to a less degree, beyond, all around it, as shown by the separate granite masses and dikes marked (and many not marked) on the map. . . . . . The typical granite of that intrusion is a rock of medium-size grains of reddish orthoclase and of round, blue quartz with a little mica, but this passes into a great variety of other rocks."

Mr. Coste holds that there has been some chemical modification of the magma in the zone of inclusions by the incorporation of the limestone and calcareous schists, but has given no details on the evidence.

Owing to the overlap of the Ordovician limestone lying unconformably on both the Archean schists and the granite, the whole story of the shattering cannot be made out at the present land surface; yet the exposure of the shatter-zone is nevertheless remarkably instructive. The general aspect of the map, the breadth of the zones, the existence of patches of the invaded formation lying isolated in the largest stock, and the numerous smaller bosses which occur like satellites about the main granite body—all lead to the conviction that the present erosion-surface is close to the position occupied by the roof of the chamber when the magma of the largest stock was solidifying.

Illustration from the geological structure near Trail, British Columbia.

The second illustration of extensive shattering at granite contacts is selected from the many that might be described from southern British Columbia. The selection has been made not because the phenomena are qualitatively different from those to be seen about other molar contacts in the region, but for the twofold reason that the shatter-zone has here been actually mapped and that the zone is wide enough to be sketched on a map of small scale. The area concerned is shown in fig. 2. It is seen to lie between the town of Trail and the 49th Parallel Boundary with the United States. It is only a few miles east of Rossland and for the most part on the right bank of the Columbia River. This little sketch-map is based on the "Trail Sheet" issued by the Geological Survey of Canada

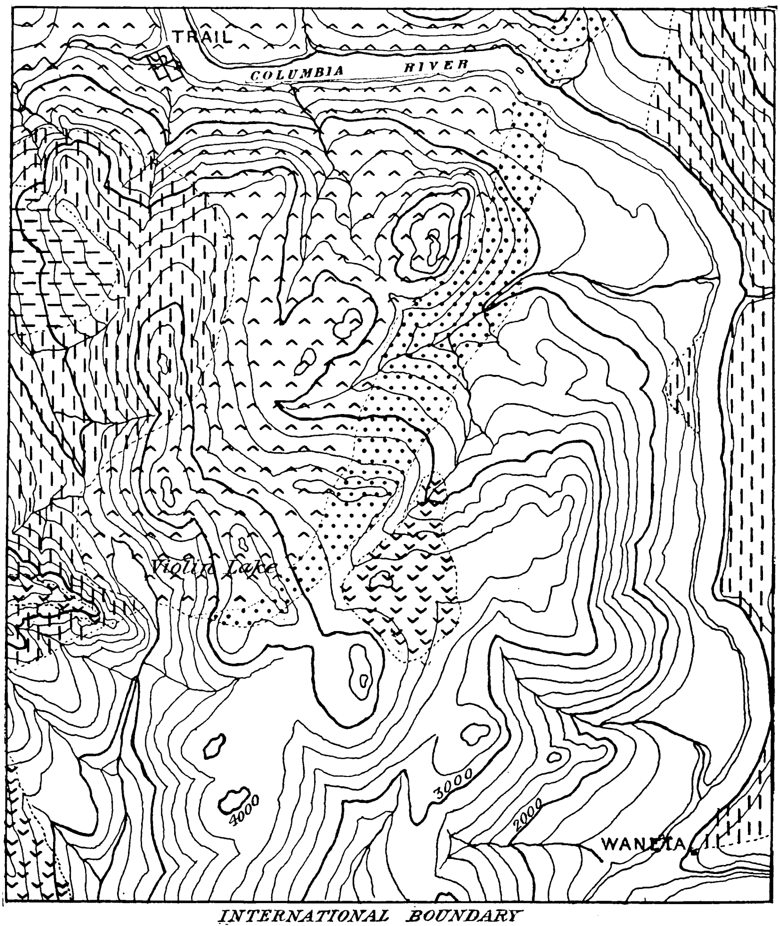

Fig. 2.

Alkaline granite.

Tonalite-granite of Nelson Batholith.

Shatter-zone of Nelson Batholith.

Rossland Basic Stock.

Rossland Volcanic Series.

Older Volcanic Series.

Scale: 1 : 95,000.

(topography by J. McEvoy; geology by R. G. McConnell, 1896) and on the writer's observations made in the same area, 1902. The heavy terrace-deposits of the Columbia Valley average nearly a mile in breadth and consequently the boundaries of the different formations are there not to be fixed with absolute precision. On account of the thick cover of drift and a dense forest, the same remark applies to the formation-limits indicated in the remainder of the area. The errors are, however, known to be of an order that cannot affect the usefulness of the map for present purposes.

The great complexity of the structure and the high degree of alteration characteristic of the rocks have put still greater difficulties in the way of defining the formations. This is particularly true of the attempt to subdivide the old volcanic rocks which form a large part of the area. There appear to be at least two volcanic rock-groups. The older is the oldest formation exposed in the area, consisting of hard, dark-colored, slaty ash beds interstratified with thick bands of squeezed and much altered basic, amygdaloidal lava-flows, and agglomerates, and cut by irregular dikes and boss-like dioritic, gabbroitic and peridotitic masses, which are probably genetically related to the lavas. As yet the required palaeontological and structural evidences as to the age and thicknesses of these rocks are lacking. In this paper the whole group may be called simply the Older Volcanic Series; the probabilities are, as suggested by McConnell, that it belongs to the Carboniferous or at least to the upper Paleozoic.

Overlying these rocks is a much younger (probably early Tertiary) formation, which, within the limits of the map, is purely volcanic—a group of greatly dislocated breccias, tuffs and flows derived from basaltic and essexitic magmas. Since this formation chiefly composes the mountains northwest, west and south of Rossland, it may be called the "Rossland Volcanic Series." There also appears on the map the eastern extremity of the coarse-grained basic rock-mass marked "gabbro" on the Trail sheet, and referred by McConnell to an origin contemporaneous with that of the Rossland effusives, probably representing the deep-seated portion of the main conduit through which these eruptions took place. This mass is highly variable and has gabbroitic, monzonitic and essexitic facies.

Both of these older series of rocks had been intensely folded, crumpled, and, in places, crushed by mountain-building forces before the intrusion of the great "Nelson batholith" took place. That huge granitic body covers an area of more than 3000 square miles. Its extreme southern end enters the area mapped in the form of a curved tongue narrowing to the southward and terminating in that direction at Violin Lake (see fig. 2).

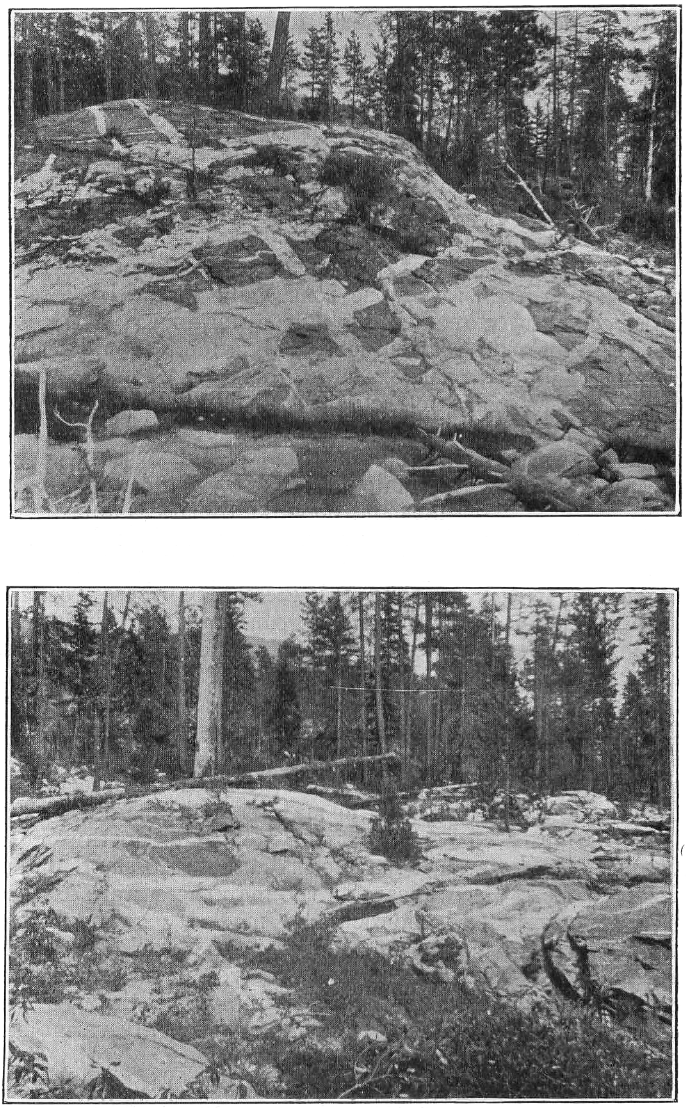

FIG. 3. Two views of the Shatter-zone, Columbia River near Trail, B. C.

Even in this small part of the batholith there is to be seen a noteworthy variability in mineralogical composition. East, west and south of Trail the rock is a gray, coarse-grained tonalite with essential andesine, biotite, hornblende, orthoclase, and accessory augite. Here and there, with apparently gradual transition, the dominant tonalite passes into a true basic to medium-acidic hornblende-biotite granite. The triclinic feldspar (again basic andesine, near $Ab_4 An_3$) here becomes quite subordinate and orthoclase assumes its position as the chief light-colored essential. Notwithstanding these and other variations in the character of the igneous body, it is to be regarded as the crystallized product of a single intrusive magma.

The shattered contact-zone which is the matter of interest in the present connection, has been crossed in three places on the line of contact running from the Columbia River to Violin Lake, and has been mapped on the basis of the information thus gained. The shatter-zone has not been mapped on the western side of the batholith since the lack of exposures made search for its limits unprofitable. It is highly probable, however, that the zone exists on that side, though it seems to be narrower than on the southeastern boundary of the granitic tongue.

An unusually fine exposure of the zone outcrops three miles below Trail on the left bank of the Columbia. The local rocks invaded by the magma are a coarse peridotite (hornblendite) and an associated gabbro, both of which apparently belong to the oldest series of rock in the area. For a distance of about 600 meters down the river and thus transverse to the molar contact, the well-washed ledges are composed of a giant breccia. Innumerable, sharply cut, angular masses of peridotite and gabbro are enclosed in the granite and are transected by many veins of the younger rock (fig. 3). The inclusions are of all sizes up to blocks ten meters or more in diameter. Three kilometers to the southwestward the shatter-zone is more than a kilometer in width; the invaded formation is diorite which is markedly schistose in many of the inclusions, becoming at times a true amphibolite. It has proved impossible to separate a zone of inclusions from the zone of apophyses because of their intimate association and because of the massive character of the rocks invaded; hence the two have been combined in the map as a zone of shattering. It is of rather extraordinary breadth in this instance but there is illustrated the same kind of dynamic action as that found along normal granitic contacts.

At the granite-peridotite contact on the river bank, many of the larger apophyses display an interesting case of differentiation. At both walls of each apophysis the essential and normally abundant bisilicates of the granite are absent or are represented by rare shreds or plates of chloritized biotite. The feldspars are here orthoclase, and microperthite with accessory oligoclase-albite. Quartz is the remaining essential. Other veins seemingly contemporaneous with these just described, are composed entirely of the same aplite. The discovery of the patent differentiation throws light on the origin of the small plutonic bodies of alkaline granite indicated on the map. The edge of one of these appears in its SW corner. That stock covers an area of about 6 square kilometers north of the international boundary and extends over perhaps as many more south of the line. The mineralogical composition, structure and specific gravity are identical with those of the aplite in veins at the river. The alkaline granite is younger than the tonalite since angular inclusions of the latter are to be found in the more acid rock, which sends strong apophyses into the tonalite-granite at various points. Many wide dikes of the alkaline granite also cut the older basic formations south and west of the batholith tongue. The two granitic types seem to have been differentiated in the deeper levels of a common magma-basin after the upper portion of the magma had consolidated.

The application of the above mentioned facts to the general problem of intrusion must be made in the light of the determinations of specific gravities. These are noted in the following table, which gives the results acquired from the use of 30 specimens taken from the granites and from fair representatives of their respective country-rocks.

Rock.	Average Spec. grav.
Tonalite	2·76
Hornblende-biotite granite	2·76
Average of batholith	ca 2·75
Lavas of older volcanic series	2·85
Dioritic rocks associated with the last	2·82
Banded ash-rocks of older volcanic series	2·79
Peridotite at contact, Columbia River	3·22
Rock of Basic Stock at Rossland	2·91
Rossland volcanic series (aver. of 8 specimens of agglomerates, tuffs and flows)	2·85
Younger, alkaline, granite stocks	2·61

It appears from the table that the rock of the main intrusive body, the batholith, is in every case of lower density than any type among the country-rocks exposed in the area. When molten the tonalite-granite would have at ordinary atmospheric pressure a specific gravity of about 2·30*. Under plutonic pressures the same strong contrast of densities between intrusive rock and invaded rocks would persist with but little change. If, then, the magma were thinly molten or even but approximating the condition of perfect fluidity, blocks rifted off from the shattered wall must sink in the magma. The presence of the existing zone of inclusions is only explicable on the supposition

* This Journal, April, 1903, p. 277.

of high viscosity in the magma in its latest phase of intrusion. By reason of the enormous pressures in depth, this strong viscosity would not prevent the injection of the magma into the shattered zone. On the other hand, the long, narrow apophyses running out to great distances from the tonalite-granite mass must have been formed in the longer period of high fluidity. To that period of maximum shattering, rifting and stoping, the opening of the magma-chamber is to be referred.

Since the specific gravity of the younger granite averages but 2·61, and since the stocks of that intrusive have invaded formations practically identical with those displaced by the tonalite-granite, the foregoing argument applies with equal or greater force to the later intrusions. The shattering is again found about these stocks, but it is much less impressive than it is along the S.E. contact of the batholith tongue—perhaps because of the smaller size and more effective stoping power of the alkaline granite bodies.

Stability of the Roofs of Magma Chambers.

The problem remains as to how far in a vertical direction such stoping has gone in the case, for example, of such an immense batholith as that represented in the Nelson granite. Did the destructive action go on until the magma had worked its way to the earth's surface? Was there at any time an extensive foundering of the thinned crust overlying the batholith? Is plutonic energy so nicely balanced with, or controlled in its exhibition by, the enormous amount of work to be performed in opening a batholith chamber that the stability of its vault is never endangered by prolonged stoping? There seems to be no evidence of such foundering and world-shaking catastrophe in the later geological ages or even in Paleozoic times. According to Kelvin's classic speculation there has occurred a great break in the history of the earth. That break was coincident with the final encrustation of the planet as it cooled from a molten state—"the date of the first establishment of that *consistentior status*, which, according to Leibnitz, is the initial date of all geological history."* Kelvin has concluded that previous to final, complete encrustation, the earth attained its present high rigidity by the submergence of the partial crusts produced by the freezing of a less dense fluid mass. The close knitting together of these foundered crust-blocks thus afforded a pre-Paleozoic earth so far cooled down, so strongly bound in its continuous crust, as not to suffer further from the catastrophic violence of wholesale crustal foundering. The speculation leads directly to the further query whether the peculiar structural complexity of the Archean

* Lord Kelvin, Math. and Phys. Papers, London, 1890, vol. iii, p. 297.

areas of the globe may not be related to that process of foundering in its latest, local phase. The refrigeration of the planet must have progressed so far even in the Cambrian period as to prevent a recurrence of life-destroying, world-circling catastrophe. In others words, the possibility of foundering depends, according to Kelvin's view, among other things, upon the amount of residual heat within the earth. By the same view the Nelson batholith takes its place among the post-Archean batholiths which may be believed to have penetrated a crust already sufficiently buttressed through secular cooling so as to withstand the strain due to the differential density of vault and molten batholith. Other general considerations relative to the problem have already been presented in the writer's first paper. All of them are offered rather to emphasize once more the difficulty and importance of the problem than to suggest that a complete solution has been found.

Geological Survey of Canada, Ottawa, Canada.