ART. III.—*The Mechanics of Igneous Intrusion.** (Third Paper;) by REGINALD A. DALY, Massachusetts Institute of Technology, Boston.

Introduction.—In the April and August numbers of this Journal in the year 1903, the writer published papers outlining the hypothesis of magmatic stoping as explanatory of the rise of batholithic magmas in the earth's crust. The hypothesis had taken form in his mind after some ten years of perplexity as to the mode of intrusion which has actually characterized granite bodies. In Vermont, New Hampshire, British Columbia and other regions he had met with this urgent and important field-problem. Everywhere the facts derived from field observations were, in principle, the same; the method of intrusion seemed, for each batholith or stock, to be the same. Since the writing of the two papers the writer has studied in some detail a dozen other large batholiths and as many typical stocks occurring on the southern boundary of British Columbia. For all of these also the stoping hypothesis appears to afford the truest explanation of the mode of intrusion.

Quite independently Barrell arrived at a similar hypothesis, as he attacked, in 1901, the problem of the "Marysville batholith" in Montana. Unfortunately his monograph was delayed in publication until 1907, so that it is only quite recently that geologists have had the benefit of this brilliant and thorough study of intrusive mechanism.† Barlow and Coleman have noted their belief in the efficiency of stoping as an intrusive process.‡ At the other side of the world, Andrews has described the great intrusive masses of New South Wales,

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* Published by permission of the Commissioner for Canada, International Boundary Surveys.

† U. S. Geol. Surv., Prof. Paper No. 57, 1907.

‡ A. E. Barlow, Ann. Rep. Geol. Surv. of Canada, xiv, Part H, p. 79, 1904; A. P. Coleman, Jour. of Geol., xv, p. 773, 1907.

and most forcibly shows the value of the stoping hypothesis and of its implied principles in explaining the rocks and field-relations in that state.*

Notwithstanding the support given the hypothesis by the work of these and other observers, the main conception has not met with favor from many working geologists.† A number of objections have been raised, most of which were discussed in the first two papers of this series. Within the last five years an unusually large amount of experimental data has been added to the confessedly meager store of known facts concerning the physics of rocks and rock-melts. These laboratory results, when fairly interpreted, seem to the writer to dispose of most of the objections. Other objections fall away as soon as they are confronted with the indisputable, long-known facts concerning rocks and igneous magmas. A third class of the objections are more stubborn and still remain among the frank difficulties of the stoping hypothesis. It is, however, the writer's belief that these difficulties are small when compared to those adhering to the older theories of batholithic intrusion.

In this third paper some of the more significant, newer contributions of the experimental laboratory to the matter at issue will be noted and discussed. In the light of the whole body of fact as understood by the writer, he will attempt to make clear the reasons why the various criticisms against the stoping hypothesis do not seem fatal to its acceptance. Finally, a new statement of certain important corollaries and tests of the hypothesis will be offered. In their discussion a certain amount of speculation seems not only warranted but necessary. It is obvious that the basis of any theory of the igneous rocks must, in part, consist of speculative assumptions; for every fruitful theory must deal with the earth's invisible interior. Neither petrology nor geology can afford to leave the problem of the earth's interior "to the poets." The advances of modern chemistry have largely been made possible through constructive speculation as to the nature of molecule and atom; yet molecule and atom are as inaccessible as the core of the earth. In the nature of the case we can never hope to arrive at the final explanation of igneous-rock bodies without building and testing hypotheses of materials and processes in and under the earth's "crust." Not only petrology but, in marked degree, mining geology is awaiting a stable theory of batholithic intrusion, since upon it must largely depend sound petrogenic and minerogenic theory.

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* E. C. Andrews, Records, Geol. Surv., N. S. Wales, vii, Pt. 4, 1904, and viii, Pt. 1, 1905.

† Cf. Science, xxv, p. 620, 1907.

Like the first and second papers, this one does not present a complete discussion of the different topics. On another occasion the writer may publish a fuller statement of the favored solution of the complex problem.

Hypothesis of magmatic stoping.—The essential points are the following:

1. Each acid, batholithic magma has reached its present position in the earth's crust largely through the successive engulfment of suites of blocks broken out of the roof and walls of the batholith.

2. The blocks (xenoliths) are completely immersed in the magma, partly through the confluence of apophyses which have been injected on joints and other planes of weakness in the country-rock; more often the blocks represent the effect of shattering, due to the obviously unequal heating of the solid rock at magmatic contacts.

3. The sunken blocks must be dissolved in the depths of the original fluid, magmatic body, with the formation of a "syntectic,"* secondary magma.

4. The visible rock of each granite batholith or stock has resulted from the differentiation of a syntectic magma.

In applying the hypothesis to the explanation of actual field-occurrences other general considerations seem necessary. Stoping and abyssal assimilation on the batholithic scale are begun by a primary basaltic magma. This magma carries the heat required for the double action.† The source of the magma is to be found in a general basaltic substratum beneath the earth's solid crust. The crust is considered as composed of two shells. The lower shell is capable of injection by huge masses from the substratum, which retains open communication with the injected bodies. The latter are regarded as then stoping their way up into the overlying shell, in which the resulting derivatives of the syntectic magma are the visible batholithic granites and allied rocks.

These subsidiary elements of the problem here to be discussed have been described in the first intrusion paper and, more fully, in a later communication on "Abyssal Igneous Injection."‡ No one of these additional conceptions is essen-

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* This very convenient name for a magma rendered compound by assimilation or by the mixture of melts, has been proposed by F. Loewinson—Lessing, Comptes Rendus, 7e session, Congrès géol. internat. St. Petersburg, 1899, p. 375.

† Whether the substratum is actually or only potentially fluid is not a vital question in this connection. T. J. J. See, as a result of his calculations, holds that the earth's interior may be fluid. He explains the observed rigidity of the planet as due not to its being a true solid but to the direct influence of gravity, which binds the earth-shells so effectively that bodily tides are almost wholly prevented. In any case rigidity and solidity are not synonymous terms. Cf. T. J. J. See, Astron. Nachrichten, v. clxxi, p. 378, 1906.

‡ This Journal, vol. xxii, 1906, p. 195.

tial to the idea of stoping *per se*. All of them may prove incorrect without invalidating the stoping hypothesis in its main feature. Combining them and the idea of stoping, the writer has constructed a general working hypothesis for the origin of the igneous rocks. It seems, therefore, expedient in the present paper to discuss the problem in its larger aspect.

Field Relations of the typical batholith.—A principal fact on which the stoping hypothesis is based has been amply illustrated in the published descriptions of granite stocks and batholiths. Most, if not all, of these bodies in their accessible portions have replaced nearly equivalent volumes of the respective country-rocks. They are generally cross-cutting bodies. Their roofs are rough domes or arches, from which large masses of the invaded rocks are sometimes pendant into the crystallized granite. In each of many cases erosion has destroyed much of the roof, and the roof-pendants, still preserving the regional strike of their structure-planes, are to-day exposed in section at the erosion-surface. Between the pendants and between the main walls of a large batholith, hundreds of cubic kilometers of country-rock formations are plainly missing; their place has just as plainly been taken by the granite.

A second principal fact is that, so far as granite batholiths and stocks are known, each of these bodies shows a cross-section enlarging with depth.* No one of them has yet exhibited a floor composed of older formations. In relation to visible country-rocks, all of them may be classed as subjacent, rather than as injected, bodies. In relation to the wall-rocks ten or more kilometers below the earth's surface, each batholith may have been truly injected as a kind of gigantic dike, but of this there is no direct proof. The actual observations in the field show unequivocally that the batholithic magmas have worked their way up by replacing and absorbing the country-rocks through the last few kilometers of ascent. Batholiths are not laccoliths.

A third generally observed fact is worthy of special attention. Where erosion has been profound the ground-plan section of the typical stock or batholith is seen to be elliptical and the profile-sections, as already noted, show that the upper-contact surface of the intrusive is dome-shaped. Both in ground-plan and in vertical sections the contact-surface is relatively smooth. Apophysal offshoots do interrupt the wall-rock, but the main-contact lines as mapped on ordinary geological maps are characteristically flowing lines. Large-scale,

*See the numerous sections of stocks and batholiths in Lepsius' "Geologie von Deutschland"; also Barrell's monograph cited, and the writer's paper on the Okanagan Composite Batholith, Bull. Geol. Soc. America, xvii, p. 330, 1906.

angular projections of country-rock into a well uncovered batholith are comparatively rare. Such smoothness of main-contact surfaces is that which is to be expected on the stoping hypothesis. A projection of country-rock would suffer specially intense shattering by the magma, which would thus tend to destroy the projection and smoothen the wall of contact. The case is analogous to the familiar exfoliation on sculptured stone in great city fires; architrave, sill, abacus and plinth lose their corners, ornaments in high relief are rifted off, and flutings are effaced. Bowlders of disintegration through weathering furnish other analogies.

In detail of form as in the larger field-relations of the typical stock and batholith, therefore, we seem to have cumulative evidence in favor of the theory of replacement and especially in favor of the hypothesis of mechanical replacement. On the other hand, the more intimate becomes our knowledge of these field-relations, the more improbable the "laccolithic theory" becomes. Neither smooth, flowing contact-surfaces against a heterogeneous terrane, nor a general elliptical ground-plan, nor an invariable downward enlargement are expected to characterize a batholith if it is simply a huge laccolith.

These summary statements are founded on the writer's field-experience, and on a tolerably wide study of the geological literature relating to granitic intrusions. The essential idea of replacement rather than displacement is far from new; it has been a lasting merit in the able work of Barrois, Michel Lévy, Lacroix and others, that they have persistently held to this fundamental fact of field-occurrence. Yet there are to-day many working geologists who just as persistently refuse to recognize the fact of the field. The chief reason for this refusal has undoubtedly been that the replacement of the country-rocks has, until recently, been attributed to their progressive solution on the main contacts—in other words, to marginal assimilation. The patent difficulties of this one view have prevented many, perhaps most, geologists from subscribing to the conclusions of their French colleagues. The proved insufficiency of the marginal-assimilation hypothesis has thus discouraged belief in that kind of replacement, but it by no means alters the fact of magmatic replacement. On the other hand, this fact will stand, no matter what theories of intrusion may prevail.

So far as recorded, the stoping hypothesis is the only one which recognizes the progressive assimilation of country-rocks as the magma rises in the crust, and, at the same time, explains the common lack of chemical sympathy between granites and their respective wall-rocks. By this hypothesis the preparation of the upper and visible part of the magmatic chamber is largely a mechanical process, working along main contacts; the solution of the engulfed blocks is effected far down in the depths of the magma—by abyssal assimilation. The resulting syntectic magma may thus be in strong chemical contrast with the adjacent wall-rock at any one level. Marginal assimilation is not excluded but is considered as an accessory and subordinate phase in the act of replacement.

Contact-shattering.—It has been objected that rocks are good conductors of heat and that, therefore, strong temperature differences with resulting rending strains are not to be expected in the shell of country-rock immediately surrounding a batholithic magma. This objection has been recently made by an expert physicist now specially engaged on petrological problems, and evidently needs consideration.* The following table of coefficients of absolute conductivity seems, however, to show, on the contrary, that rock-matter is far from being ranked as a good conductor. The table has been made by compiling the values noted in the Landolt-Börnstein's Physikalisch-chemische Tabellen (1905 edition) and in Winkelmann's Handbuch der Physik. The values for the rocks are of the order expected in view of the familiar proofs of the extremely slow cooling of lava-flows.†

	k
Silver, about	1·0000
Copper, "	·9480
Lead	·0836
Quartz	·0158
Marble	·00817
Granite	·00757 –·00975
Gneiss	·000578–·00817
Sandstone	·00304 –·00814
Basalt	·00673
Syenite	·00442
Glass	·00108 –·00227
Water, about	·00130
Paper	·00031
Flannel	·00023
Silk	·00022
Cork	·00013
Feathers	·0000574

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* Cf. A. L. Day, Science, xxv, p. 620, 1907.

† The steepness of the possible temperature gradient in the wall-rock is shown by the fact that, a few days after lava ceases flowing, one can walk on its crust, although the lava just below is at red heat (700°-950° C.) or is yet hotter. For many hours or for several days the gradient at the surface may equal or surpass 500° C. per foot.

In the manufacture of calcium-carbide a mixture of limestone and coke is submitted to the action of a powerful electric arc. At the end of a furnace-run (about fourteen hours in the plant at Ottawa, Canada) the flow of heat is nearly steady and the temperature gradient in the furnace is about 3000° C. per foot. In this case the diffusivity of the limestone-coke mixture in the interior of the thoroughly heated furnace must be well below 60 in the Kelvin system of units.

Weber has found that k for gneiss at 0° C. is 0·000578 and at 100° C. 0·000416, showing a very great lowering with increase of temperature.* In fact, through the interval 0°–100° C., k seems to vary about inversely as the absolute temperature.† If this law should hold to 1100° C. the conductivity of average rock at 1100° falls to about 0·001—nearly the value for water, which is famous as a poor conductor.

In the present connection the thermal diffusivity (κ) of rock, rather than its conductivity, is of first importance. If s = specific heat and d = density, we have

$$\kappa = \frac{k}{s.d}$$

For rock at room temperature (20° C.) Kelvin assumed 400 as the value of κ when the unit of length is a foot, the unit of time a year, and the unit of temperature one degree Fahrenheit. This value is close to that which represents the average of the determinations made for different rocks at room temperatures, during the years since Kelvin wrote his famous essay.‡

If κ be assumed as 400 at all temperatures up to 1300° C., it is possible to calculate the temperature gradient in the wall-rock of a molten batholith at the end of specified periods of time. For practical purposes the surface of contact may be regarded as infinite; let it further be considered as plane. Under these conditions the following Fourier equation furnishes the datum for calculating the temperature at a point x feet from the contact at the end of t years.§ In the equation b = the temperature of the magma; c = the temperature of the wall-rock assumed as initially uniform; and u = the required temperature. We have:—

$$u = b + (c - b)\,\frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{\kappa t}}} e^{-\beta^2}\, d\beta.$$

For values of $\frac{x}{2\sqrt{\kappa t}}$ which are less than 2·6 the value of the integral can be readily found from the table of the probability integral which appears in standard text-books on the Method of

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* Values taken from Landolt-Börnstein Phys.-Chemische Tabellen. Forbes and Hall have proved analogous relations for iron and for magnesium oxide; cf. J. D. Forbes, Trans. Roy. Soc. Edinburgh, xxiv, p. 105, 1867, and E. H. Hall and others, Proc. Amer. Acad. Arts and Sciences, xlii, p. 597, 1907.

† Cf. P. G. Tait, Recent Advances in Physical Science, 2d ed., London, p. 270, 1876.

‡ Trans. Roy. Soc. Edinburgh, 1862.

§ Cf. W. E. Byerly's Elementary Treatise on Fourier's Series, Boston, 1893, p. 86.

Least Squares. For higher values of $\frac{x}{2\sqrt{\kappa t}}$ the value of the integral can, in many cases, be computed by developing it into a series. Kelvin's value for κ is peculiarly favorable for such computation and the corresponding units have been used by the writer in the calculations.

Let b = 2200° F. (about 1200° C.); c = 400° F. (about 200° C.); t = 1, 4, 16, and 100 years; and let x have the different values shown in the left-hand column of the following table (I) The corresponding temperatures are shown in the other columns.

TABLE I.—Showing values of u when $\kappa = 400$ and

x	$t = 1$ year.	$t = 4$ years.	$t = 16$ years.	$t = 100$ years
0′	2200° F.	2200° F.	2200° F.	2200° F.
10′	1703	1947	2074	
20′	1263	1703	1947	
40′	683	1263	1703	
80′	408 5	683	1263	
100′	ca.400	537	1078	1703
160′	400	408·5	683	
200′	400	ca.400	537	1263
320′	400	400	408.5	
400′	400	400	ca.400	683

The table shows that, at the end of the first year, the temperature of the rock is but slightly affected by the magmatic heat at a point 80 feet from the contact, and that the temperature gradient for the 80-foot shell then averages nearly 23° F. per foot. At the end of four years the temperature is but slightly affected at a point 160 feet from the contact and the temperature-gradient is about 11° F. per foot.

But κ cannot be nearly so great as 400 in the case before us. We have seen that k decreases rapidly with rise of temperature in rock. The experiments of Weber, Bartoli, Roberts-Austen and Rücker, and Barus show that the specific heat of rock averages about ·180 at 20° C. and increases regularly with rise of temperature, so that at 1100° C. the specific heat averages about ·280.* It follows that thermal diffusivity in rock decreases with rising temperature even faster than the conductivity decreases. At 1100° C., κ may, indeed, be only

$$\left(\frac{\cdot 180}{\cdot 280} \times \frac{293}{1373} \times \frac{1\cdot 000}{\cdot 973} =\right) 0\cdot 141$$

or less than one-seventh, of the diffusivity at 20° C. For rock heated to 1000° or 1200° C. κ is, thus, probably not much more than 60 in the Kelvin system of units.

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* For references see J. H. L. Vogt, Christiania Videnskabs-Selskabets Skrifter, I. math.-naturv. Klasse, No. 1, p. 40, 1904.

It seems safe to assume, first, that the diffusivity of the gradually heated wall-rock may vary from 275 or less to 100 or 150; secondly, that the average diffusivity of an 80-foot shell heated during the first year by adjacent molten magma, will be no greater than 200. If κ be regarded as averaging 200 for all periods greater than one year, the four columns showing values of u in the table will serve if t is, respectively, 2, 8, 32 and 200 years.

As a result of somewhat rigorous calculation, then, it appears certain that the heating of wall-rock by plutonic magma must progress with great slowness and that the resulting temperature gradient in the shell adjoining the molten magma must be steep for many years after the original establishment of the contact.*

Further, Less has proved that rocks have highly variable coefficients of conductivity, some species possessing coefficients twice as high as those of other species.† It is also well known that bedded or schistose rocks conduct heat along and across their structure-planes at quite different rates. Where, therefore, the wall-rocks about a batholithic mass are heterogeneous, the heat-conduction is variable and expansional stresses must ensue.

A rough calculation of the enormous stresses involved in all these processes of differential heating was published in the second paper of this series, where also an account is given of the practical use which has been made of such stresses in primitive quarrying.‡ Every great city conflagration leaves manifold evidences of the shattering effects of the one-sided heating of a rock-mass—in columns, sills, and cornices of granite or sandstone.

There seems, therefore, to be a sheer necessity for believing in contact-shattering through differential heating and expansion in the thin shell of a country-rock which encloses a large body of molten magma. The evidence for the shattering is often exceedingly full and clear in the field. The broad or narrow belts of xenoliths so often found just inside the main contacts of batholiths are very hard to explain if those batholiths are due to laccolithic injection. The blocks are characteristically angular; they are generally not arranged with their longer axes parallel, as if they had been pulled off from the

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* By using the same Fourier equation it is not difficult to show that the loss of thermal energy which a magma suffers by conduction into the country-rock is relatively small, even after the lapse of two or three hundred thousand years. The long duration of the magmatic period in a slightly superheated plutonic mass of large size becomes easily understood.

† Phil. Trans., vol. clxxxiii A, p. 481, 1892.

‡ This Journal, xvi, p. 112, 1903; cf. Ann. Rep. State Geologist of New Jersey, 1906, p. 17.

walls by the friction of the moving magma. On the laccolithic theory one would expect many of the xenoliths to form elongated smears in the granite rock. This is indeed occasionally seen but most exceptionally; as a rule the xenoliths have just that irregularity of form and arrangement which they should have if they had been shattered off by the hot magma just before its final consolidation. Throughout its long, earlier history the magma must, in every case, have had a much more effective shattering power.

It may be noted that the shattering of crystals and rock-fragments, when immersed in silicate melts, has often been observed.* The strains are, in such cases, necessarily of a lower order than those developed on the wall of a batholith where, therefore, shattering is even more certainly brought about.

Relative densities of magma and xenolith.—In his first intrusion-paper, the writer published the results of his attempt to calculate the possible specific gravities of the chief types of molten magmas under plutonic conditions. The calculations were based on Barus's well-known fusion experiments on diabase. The specimen investigated had a specific gravity of 3·0178; when fused to a glass and cooled to 20° C., a specific gravity of 2·717. He further states that the glass† showed an expansion of 3·9 per cent in "melting" and, as glass, expanded 0·000025 in volume for a temperature rise of 1° C. through the interval 0°–1000° C. and 0·000047 in volume for 1° C. through the interval 1100°–1500°. The "melting" expansion (solidification-contraction) and the varying rate of expansion (or contraction) above and below 1000° C. seem to show that some crystallization of the melt took place during the experiment. Such crystallization was inevitable under the conditions of the experiment, in which the cooling lasted several hours. Barus's curves do not, therefore, show directly the volume changes suffered by pure diabase glass in passing from the molten isotropic state to the rigid isotropic state at room temperature. Excluding the "solidification" contraction, the glass loses but 3·5 per cent of its volume in passing from the molten state at 1400° C. to room temperature; the loss of volume through the same temperature interval was calculated in the first paper as about 8 per cent. Barus found that the net decrease in specific gravity in passing from rock at 20 C. to glass at 20° C. was 10 per cent. For his diabase specimen, therefore, the decrease of specific gravity in passing

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*Cf. C. Doelter and E. Hussak, Neues Jahrb. für Min. etc., 1884, p. 18; A. Becker, Zeitschr. d. d. geol. Ges., xxxiii, p. 62, 1881.

† "Throughout this paper the molten rock solidifies into an obsidian." C. Barus in Bull. 103, U. S. Geol. Surv., p. 26, 1893.

from 20° C. to molten condition at 1200° C. is possibly only about 13 per cent, instead of about 16 per cent, as noted in the first paper.[*]

Quite recently J. A. Douglas has made a number of very careful measurements of the densities of typical igneous rocks and of their respective glasses, all specific gravities being taken at room temperatures.[†] Douglas's method is reliable and his results accordant. For gabbro he found the decrease of specific gravity, in passing from rock to glass, to be 5·07 per cent. Delesse had found the decrease to be 11·46 per cent, as the average of measurements of two specimens from different localities Barus's determination, 10 per cent, is intermediate between the two.

It seems probable, therefore, that a decrease of 6 per cent in specific gravity (rock to glass at 20° C.) is close to the minimum for the average gabbroid rock, and it is possible that Barus's 10 per cent decrease is too high for average gabbro. For present purposes it is safer to use the minimum value of 6 per cent. Similar minima for diorite (6 per cent), quartz diorite and tonalite (7 per cent), syenite (8 per cent) and granite (9 per cent) have been estimated from the numerous measurements of Delesse, Cossa and Douglas. Each of these rocks certainly

TABLE II.

	Specific gravity of Crystalline rock at			Specific gravity of same rock when molten at			
	20°C.	1000°C.	1300°C.	1000°C.	1100°C.	1200°C.	1300°C.
Gabbro and diorite	2·80	2·73	2·71	2·57	2·56	2·54	2·53
	2·90	2·83	2·80	2·66	2·65	2·64	2·63
	3·00	2·92	2·90	2·75	2·74	2·73	2·72
	3·10	3·02	3·00	2·84	2·83	2·81	2·80
	3·20	3·12	3·10	2·94	2·92	2·91	2·91
Quartz-diorite and tonalite	2·70	2·63	2·61	2·46	2·45	2·44	2·43
	2·80	2·73	2·71	2·54	2·53	2·51	2·51
Syenite	2·60	2·54	2·52	2·33	2·32	2·31	2·31
	2·70	2·63	2·61	2·42	2·41	2·40	2·40
	2·80	2·73	2·71	2·52	2·51	2·50	2·50
Granite and gneiss	2·60	2·54	2·52	2·31	2·30	2·29	2·29
	2·70	2·63	2·61	2·40	2·39	2·39	2·38
	2·80	2·73	2·71	2·49	2·48	2·47	2·47

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[*] Bischof, in 1841, found that basalt expanded 7 per cent in passing to a glass at room temperature, and 10·4 per cent in becoming molten. (Quoted from Zirkel's Lehrbuch der Petrographie, 2d ed., 1893. vol. i, p. 683.)

[†] Quart. Jour. Geol. Soc., xiii, p. 145, 1907.

expands in the interval 20°–1300° C. as much as 0·000025 volume per degree Centigrade (Barus and Reade—see first paper). This average may safely be employed as a means of determining the minimum decrease of density which each rock-type undergoes in passing into the molten condition. On this basis the writer has constructed the preceding table (II), which shows the changes of specific gravity at convenient temperature intervals.

Table III shows the changes in specific gravity undergone by blocks of stratified and schistose rocks (common country-rocks about batholiths), as these blocks assume the temperature (1300° C.) of molten magma in which they are immersed.

TABLE III.

	Range of sp. gr. at 20°C.	Range of sp. gr. at 1300°C. (solid)
Gneiss	2·60–2·80	2·52–2·71
Mica schists	2·75–3·10	2·67–3·00
Sandstone	2·20–2·75	2·13–2·67
Argillites	2·40–2·80	2·32–2·71
Limestone	2·65–2·80	2·57–2·71

It appears from these tables that nearly all xenoliths must sink in any molten granite or syenite; most xenoliths must sink in molten quartz-diorite, tonalite or acid gabbro. Many xenoliths might float on basic gabbro but the heavier schists and gneisses must sink in even very dense gabbro magmas at 1300° C.

Giving, then, the highest permissible values to the specific gravities of magmas, it is still true that blocks, such as are shattered from the wall or roof of a batholith, must sink when immersed in most magmas at atmospheric pressure. As shown in the first intrusion paper, the blocks would likewise sink, though the magma enveloping them lies at depths of ten or fifteen kilometers below the earth's surface.

Sinking of the shattered blocks.—It has been objected to the stoping hypothesis that the viscosity of granitic magmas is too great to allow of the sinking of blocks even much denser than those magmas.* This objection has, however, never been sustained by definite experimental or field proofs. The xenoliths visible along batholithic contacts have assuredly not sunk far from their former positions in wall or roof and the reason for this must be sought in the high viscosity of the magma. High viscosity is an essential attribute of a nearly frozen magma. The phenomena of fractional crystallization and of magmatic differentiation unquestionably show that each

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* Cf. W. Cross, G. F. Becker, and A. L. Day, Science, xxv, p. 620, 1907.

plutonic magma must pass through a long period of mobility. The most viscous of granitic magmas, the rhyolitic, issues at the earth's surface with such fluidity that the rhyolite often covers many square miles with a single thin sheet. The absolute viscosity of the Yellowstone Park rhyolites must have been of a low order when many of these persistent flows were erupted.*

Even granting that the kinetic viscosity of a plutonic magma is thousands of times that of water, it seems inevitable that it could not support xenoliths more dense than itself. In a few days or weeks stones will sink through, and corks will rise through, a mass of pitch, the viscosity of which is more than a million of millions of times that of water.† Ladenburg has lately shown that small steel spheres will, in a few minutes, sink through twenty centimeters of Venetian turpentine, a substance 100,000 times as viscous as water.‡ Ladenburg's experiments have verified the generally accepted equation expressing the rate of sinking of a sphere in a strongly viscous fluid:

$$x = \frac{2}{9} \frac{gr^2 (d - d')}{v}$$

were x = the velocity of the sphere when the motion is steady; g = the acceleration of gravity; d = the density of the sphere; d' = the density of the fluid; r = the radius of the sphere; and v = the viscosity of the fluid.§ The equation shows that the velocity of sinking varies directly as the square of the radius of the sphere. This fact may be correlated with the observation so often to be made on granite contacts, that large xenoliths are rare. This apparently means that, at the end of the shatter-period, the viscosity is truly so high as to allow of the smaller blocks being trapped at high levels in the freezing magma, while the large blocks, with greater velocity, shall have sunk into the depths.

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*See Atlas accompanying Monograph 32 of the U. S. Geol. Survey. King described the great rhyolite flows of Nevada as bearing "abundant evidence of true fluidity at the period of ejection." U. S. Geol. Explor. 40th Parallel. Sys. Geol. 1878, p. 616.

Doelter has studied the behavior of a large number of crystalline rocks and minerals during fusion. His results show that the temperature-interval between the stage of softening and that of notable fluidity averages, for the basic rocks, about 50° C., and for the acid rocks, about 90° C. (Tscher. Min. u. Petrogr. Mitth. xx, p. 210, 1901.) The interval is not great and it certainly seems unsafe to deny that even the most viscous, because cooled, lavas were fluid in depth.

†Jamin et Bouty, Cours de Physique, tome I, 2e fascicule, Paris 1888. p. 135; cf. Daniell's Text-book of the Principles of Physics, 2d ed., London, 1885, p. 211.

‡Annalen der Physik, xxii, p. 287, 1907.

§Poynting and Thomson, Text-book of Physics, Properties of Matter. London, p. 222, 1902.

Doelter estimates that the pressure of from 7500 to 11,000 meters of rocks increases magmatic viscosity no more than 20 to 30 per cent.* If the increment be anywhere near this value we may be certain that the viscosity of superheated, plutonic magma is relatively low. Becker has calculated that the viscosity of a Hawaiian basaltic flow, not one of the most fluid, was, at eruption, about fifty times that of water. The more fluid rhyolite flows may have viscosity a thousand times greater than that of water. The corresponding viscosities of the same magmas when ten kilometers underground may, then, be possibly no more than from sixty to fifteen hundred times that of water. One must conclude that a xenolith, even very slightly denser than such a plutonic magma, must sink into it. Since such magmas necessarily cool with extreme slowness, there is evidently good ground for believing that an enormous amount of solid rock could be engulfed before practical rigidity is established. The average xenolith must sink in a less dense magma with the viscosity of pitch—yet how much more rapidly in magma possessing the low viscosity which is postulated in any of the ruling theories of plutonic-rock genesis!

Problem of the cover.—The stoping hypothesis presents an obvious principal difficulty; it refers to the apparent danger of the foundering of the roofs covering the larger batholiths. Under plutonic conditions (at depths of from three to ten kilometers) the average molten granite would have a specific gravity no higher than 2·40. The average rock of its roof has a specific gravity of about 2·70. If, then, through orogenic movement, a large mass of the roof-rock became once wholly immersed in the granite, it would not only founder itself but through subsequent buckling the whole roof might collapse and founder in sections. Such a catastrophe has almost certainly not happened in the case of any Paleozoic or later batholithic intrusion. This difficulty has been emphasized by Barrell, who has justly given it a prominent place in his monograph.† Lawson speaks of batholiths 100 miles in diameter and also finds the necessity of explaining their roof-support as a principal ground of unfavorable criticism.‡

The present writer cannot claim to have solved this problem, but he does not find it to form a fatal objection to the hypothesis. In the first place, it seems clear that all the other hypotheses of granitic intrusion are facing the same dilemma. All of them expressly or tacitly postulate some degree of fluidity in each granitic mass as it either replaces or displaces

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* Physikalisch-chemische Mineralogie, Leipzig, p. 110, 1905.

† Op. cit., p. 172.

‡ Science, xxv, p. 620, 1907.

its country-rocks. We have seen that, though the viscosity of such a magma may be several hundred times that of water, the roof-sections, once immersed, must sink in the magma. All petrologists who believe in magmatic or other differentiation as operative in batholiths must face the common difficulty.

Secondly, the writer has shown reasons for believing that the earth's crust at present rests on a continuous *couche* of basaltic (gabbroid) magma, either quite fluid or ready to become fluid when injected into the crust. If the average specific gravity of the crust is 2·75 (a probable value), it would as a whole be quite able to float on the basaltic *couche*, which, as noted in Table II, would probably have a specific gravity over 2·90. Imperfect as the numerical data are, we seem justified in concluding that the earth's crust is now, as a whole, in stable flotation.*

It may have been entirely different in pre-Keewatin (earliest Archean) time when the superficial, acid *couche* of the primitive earth began to solidify. Then foundering may have taken place, as Kelvin imagined, and the early formed crusts could have sunk a score of kilometers or more until they met the denser *couche* below. Possibly some of the complexity of the pre-Cambrian formation may be referable to this unstable condition of the early crust. Already in Keewatin times the acid shell was solidified and was then penetrated by basaltic injections which reached the surface, forming the heavy masses of greenstones belonging to that period. Since then the crust has remained essentially coherent, and through it the primary basalt has, at many times and places, been erupted. It is, however, quite possible that the lack of system among the axes of the Laurentian batholiths and the abundance of those batholiths are both explained by the thinness and weakness of the crust in post-Keewatin and pre-Cambrian time.

For Paleozoic and later batholiths there is a well-defined law that they have penetrated the crust only on the sites of folded geosynclinals, and that the larger batholithic axes are usually arranged parallel to the respective geosynclinal and mountain-range axes.

In other words, the intrusion-history of the globe may be conceived as divisible into three epochs: the first being that in which the outer primary shell was becoming stable through successive solidifications and founderings; the second being the post-Keewatin (Laurentian) epoch of very general interaction between the fluid basaltic substratum and acid crust, without extensive founderings but with development of many large, irregularly occurring batholiths; the third, a period of the localization of batholiths in certain mountain-built belts,

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* For a further discussion of this point see this Journal, xxii, p. 201, 1906.

where alone there seems, in this third period, to have occurred the injection of molten magma in masses of batholithic size—in no known case accompanied by wholesale foundering.

Again, granting the hypothesis that a visible post-Archean batholith is the acidified, upper portion of a basaltic body originally injected to a level less than about ten or fifteen kilometers from the earth's surface (perhaps the level of no strain), it is not difficult to see that extensive foundering may be impossible. Only after some differentiation or acidification of the primary magma would any part of it become less dense than the average roof-rock. Xenoliths of the heavier gneisses and schists would, however, sink. When dissolved in the primary magma their material—added to that dissolved along the main contact-surfaces—would lower the density and inaugurate the stage of general stoping. Only when the resulting syntectic magma has been formed in large amount is there any danger of roof-foundering. But it is evident that, in the process of dissolving the engulfed blocks, the magma is losing heat. In every post-Archean batholith the magma, because of exhaustion of the heat-supply, seems to have been arrested in its upward course at average distances of one or more kilometers from the earth's surface. The syntectic magma, less dense than the roof-rock, is thus necessarily of limited depth. That depth represents the thickness of the *couche* which endangers the stability of the roof. If, now, we imagine the buckling of the roof with the complete immersion and sinking of certain parts of it, the foundering must be limited by the width of the injected body (seldom over fifty kilometers) and by the thickness of the acid *couche* (ten kilometers or less). Extensive floods of rhyolite and allied rocks may have issued at the surface in consequence of partial foundering (faulting), but great crustal catastrophes involving large areas would not be expected.

Finally, it should be noted that post-Archean granitic intrusions have regularly followed periods of prolonged orogenic crushing, during which accumulated tangential stresses are effectually relieved. As the magmas work their way up into the folded terranes there is relatively little chance for the buckling of the roof. Until it is buckled and immersed in the magma it cannot sink. Now the heat of the magma, though it shatters the roof-rock at the immediate contact of solid and fluid, must tend to expand the roof, tighten it, prevent normal faulting and so strengthen the roof. The cover of the batholith is thereby kept in an exceptionally rigid condition. Its strength is, initially, that of a domed shell spanning diameters not very many times the thickness of the shell. The strength is increased, as with the groined roofs and arches of Gothic architecture, by the presence of roof-pendants ; and by thermal expansion, the whole is strongly knit together. Immersion and foundering of roof-sections may, therefore, not have been possible in the case of post-Archean batholith or stock.

In spite of the highly theoretical nature of some of the foregoing argument, it appears to the writer to carry weight enough to warrant our regarding the difficulty in question as not destructive of the stoping hypothesis. The problem needs further study in connection with this and all other conceptions of granitic intrusion.

Supply of the necessary heat ; magmatic superheat and its causes.—Whether the observed average temperature gradient within the earth's crust is to be explained as due to original heat (inherited from an early epoch in the development of the earth either from a gaseous or planetesimal nebula), or whether the gradient is due to the evolution of heat with the break-up of radium and other radio-active substances, are general questions not immediately affecting the stoping hypothesis. We need go no further back in the thermal problem than to secure an estimate of the minimum temperature of the primary magma when abyssally injected and thus prepared for stoping and assimilation. This estimate is evidently not easy to make. A rough idea of the probable temperature may be obtained by deductively considering the temperature gradient or, secondly, by assuming that the initial temperature of the abyssally injected basalt is not far from that of the hottest basaltic lava known in volcanoes.

The first method is only applicable on certain assumptions as to the thermal and material constitution of the basaltic substratum. It is first of all assumed that the substratum, though a true basalt for many kilometers of depth, is faintly stratified according to density differences. The chemical contrast between successive shells of the substratum may be extremely slight and yet sufficient to prevent convection-currents, even though the bottom shell of the substratum is several hundreds of degrees hotter than the uppermost shell. A rise in temperature of four hundred degrees involves an expansion of only about one per cent in volume. An underlying *couche* of basalt at 1600° C. would, therefore, if its specific gravity at 1200° C. were 2·93, not convectively displace an overlying *couche* of magma at 1200° C. and with a specific gravity of 2·90. Such faint density stratification, if assumed, goes far to explain the general stability of the earth's crust and so far is in accord with the facts of post-Archean geology. This conception also involves the possibility that the observed temperature gradient continues without important change, deep into the substratum. It is here also assumed that the gradient, 3° C. for 100 meters of descent, applies to the crust and to the upper part of the substratum at least. It must be noted, however, that the gradient may very considerably steepen in the depths, because of the fact that the thermal conductivity and diffusivity of rock both decrease in large ratio with increase of temperature. The amount of steepening of the gradient is unknown, but our ignorance on this point is unessential to the principle of the following argument, in which the normal gradient is assumed throughout.

Thirdly, it is assumed that, under normal conditions, the substratum shell immediately below the solid crust is not superheated but is at the melting-point of basalt at that depth. The accepted temperature gradient gives, at the depth of 38 kilometers, a temperature of 1140° C. Vogt has calculated that the pressure at this level raises the melting-point about 50° C. Since basalt at atmospheric pressure is just melted at about 1190° C., we may conclude that the bottom of the crust, in accordance with the assumptions, averages 38 kilometers below the present surface. If the earth is cooling down, the crust was evidently somewhat thinner during Tertiary and pre-Tertiary batholithic intrusion.

If, now, a broad geosynclinal prism of sediments, 10,000 meters thick in the middle, is laid down on the site of a future mountain-range, the isogeotherms must rise. The uppermost layer of the substratum, where most deeply buried, will thus tend to assume a temperature of nearly 300° C. above normal. If the sedimentary prism be folded and overthrust as in the usual large-scale orogenic disturbance, the substratum below the mountain-range may be still more effectively blanketed, with a further rise of the isogeotherms. Quickened erosion may, however, largely offset this thickening by the mountain-building process, and it would be unsafe to postulate a total rise of temperature of more than 300° C. in the substratum of the area. Part of this superheat is lost by conduction into the crust, the lower basic part of which may be thus melted. An unknown but possibly considerable fraction of the total superheat may remain in the original substratum, and this amount of superheat would characterize the basalt when rapidly injected into the crust.

In the partial release of pressure in the act of injection we have another, but probably less important, source of superheat—averaging some fraction of the 50° C. by which the melting-point is raised at the bottom of the 38-kilometer crust. A third source of superheat is found in the conversion into heat of the mechanical energy necessary for injecting a viscous melt into an opening cavity.

These three sources of superheat would alone furnish enough thermal energy to raise the injected basaltic magma from 1140° C. to some temperature short of 1500° C. or 1600° C.

The piling up of 10,000 meters of lava over a large area would have an analogous superheating effect on the substratum. This conclusion enables us to give some explanation of the fact that the lavas of Kilauea and Mauna Loa seem to be the hottest known in any volcanic vent. The vast Hawaiian lava-plateau has, apparently, been built up by the comparatively rapid effusion of basaltic flows from Pacific depths averaging 6,000 meters to heights above sea of about 4,000 meters. The unique lava-fountains of the calderas, while showing obvious evidence of considerable superfusion, are described as glowing with "white heat."* If a correct description, this implies a temperature of 1300° C. or possibly 1400° C.† Such temperature must be a minimum for the substratum which feeds the calderas, where there is continuous loss of heat in the convectively stirred lava.

Speculative argument and limited observations in nature agree, then, in fixing some such temperature as 1300° C. as a minimum for the basaltic mass injected into the crust-rock below a great mountain range.

Capacity of superheated, plutonic magma for melting and dissolving xenoliths.—Basalt must have a thermal capacity much like that of diabase at the same temperature. Barus's experiments show that the average specific heat of diabase for the interval 1300–1140° C. is ·350.‡ The heat-energy contained in the substratum, if it be superheated 160° C. above its melting-point (1140° C.), is in excess of that contained in the substratum just above its melting point by (160×·350=) 55+ gram-calories.

This surplus heat-energy is available for the fusion and assimilation of country-rock. There are good reasons for believing that the average wall-rock of granite batholiths has the composition and crystallinity of a granitoid gneiss. For purposes of calculation this will be assumed to be the fact. The average temperature of the wall-rock before an abyssal intrusion may be conservatively estimated from the normal temperature gradient to be 200° C. In order to raise the gneiss to the temperature of 1200°, where it is just molten,

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* J. D. Dana, Characteristics of Volcanoes ; New York, 1891, p. 200.

† LeChatelier and Boudouard's High Temperature Measurements : New York, 1904, p. 246.

‡ C. Barus, op. cit., p. 53. For the interval 100–20° C. the mean specific heat is about ·185. There is, in fact, a steady increase in the mean value as the temperature of any silicate or silicate mixture rises. This fact goes far to explain the prolonged liquidity of assimilating magmas. Cf. J. H. L. Vogt in Christiania Videnskabs-Selskabets Skrifter, math-naturv. Klasse, 1904, No. 1, p. 40.

about 410 calories (assuming latent heat at 90 calories—a value estimated by Vogt for the silicates) per gram must be supplied from an outside source. If all the superheat of the basalt were available for melting (not dissolving) gneiss, $\frac{55}{410}$ of mass-unit of gneiss would be melted by mass-unit of the superheated basalt; or about 7·5 mass-units of the basalt would melt a mass-unit of wall-rock.

Such simple melting would, however, not occur. There are plenty of field and laboratory proofs that molten basalt, even slightly superheated, will dissolve fragments of gneiss and allied rocks. The mutual solution of two contrasted silicate mixtures takes place at a certain temperature which is lower than the melting point of either one. The simple contact of two such materials suffices to cause their mutual solution at that lower temperature.* This fundamental law of physical chemistry has been experimentally demonstrated for silicates by Vogt and by Doelter and his pupils, although the last mentioned authors have, perhaps, not sufficiently regarded the fact that it takes considerable time for the mutual solution to take place.†

Petrasch has experimentally shown that, when two parts of limburgite and one part of granite are mixed and heated, they melt together at 950° C. and the solution remains fluid down to 850° C.‡ Predazzo granite softens at 1150° C. and the limburgite at 995° C.§ In this case, there is a lowering of 200°–300° below the melting-point of granite and 45°–145° C. below that of limburgite.

It seems highly probable, thus, that gneiss-xenolith and basalt would form a solution or syntectic film which is molten at a temperature *at least* 50° C. below the fusion-point of basalt at the average depth of ten kilometers or less below the earth's surface. At those depths basalt melts at about 1100° C.; the syntectic would be molten at or below 1050° C. If the syntectic film were continuously removed during the sinking of the block or by the currents inevitably set up during stoping,

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*Cf. O. Lehmann, Wiedemann's Annalen der Physik, vol. xxiv, p. 17, 1885.

†See J. H. L. Vogt, Christiania Videnskabs-Selskabets Skrifter math.-naturv. Klasse, 1904, No. 1, p. 191; and Tscherm. Min. u. Petrogr. Mitth., xxiv, p. 473, 1906.

‡K. Petrasch, Neues Jahrb. für Min., etc., Beil. Bd. xvii, 1903, p. 508. Petrasch mixed the powders of one part of granite (softens at about 1150° C.) with two parts of hornblende-andesite (softens probably about 1050° C.) and found the mixture to become molten at 900° C., proving again an important lowering of the melting-point below that of either rock. Basic rock thus acts as a flux for granite (or gneiss) to an extent comparable with that proved by Petrasch and others for lithium chloride, calcium fluoride, ammonium chloride, sodium tungstate, etc.

§C. Doelter, Tscherm. Min. u. Petrogr. Mitth., xx, 1901, p. 210.

nearly all of the superheat of the basalt might be used in dissolving the gneiss. The total melting-heat of gneiss, if molten at 1050° C., would be about 400 calories. The heat-energy required for the solution of one gram of the gneiss which has an original temperature of 200° C. is (400 − 40 =) 360 calories. The heat-energy given off by one gram of basalt in cooling from 1300° to 1050° C. is about (250 × ·340 =) 85 calories. One gram or mass-unit of gneiss would, then, be dissolved by $\left(\frac{360}{85}=\right)$ 4·3 grams or mass-units of the primary basalt, provided all the thermal energy were used for solution.

These various calculations are obviously very crude. They take no account of conduction of heat away from the batholithic mass, nor any account of possible exothermic or endothermic chemical reactions between basalt and wall-rock; nor any account of the influence of water, chlorides, etc., derived from the geosynclinal rocks which are assimilated.* These substances held in the magmatic solution tend to lower the solidification point of the syntectic. The result of the calculation would also be affected if we assume that the heavier xenoliths would sink to levels where the temperatures are above 1300° C. Finally, the result would be different if we postulate that the invaded formations, through the crushing incident to orogenic movement before the intrusion, had been heated above 200° C. Without here entering on the discussion of these further complications, we may conclude that probably from four to six volumes of the superheated primary basalt would furnish the heat-energy necessary for the solution of one volume of wall-rock.

If this rough estimate is even approximately correct, we have some idea of the actual assimilating power of plutonic magma which has been superheated a couple of hundred degrees. We also see a definite reason for the fact that post-Archean granites have never, so far as known, stoped their way to the earth's surface. The crust has been too thick, the expenditure of heat-energy in forming the syntectic magma too vast, that the process could operate to its extreme and so endanger the stability of the crust-roof above each batholith.

Objection founded on rarity of evidences of assimilation at observed wall-rocks.—One of the most commonly expressed objections to any theory of the replacement of invaded for-

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* According to the stoping hypothesis almost all of the heat conducted into the shells of country-rock successively stoped away during the magmatic period, is not lost, but is available for the abyssal assimilation of the engulfed blocks. In view of the slowness with which the mixtures of powdered silicates melt, it is probable that notable exothermic reactions do not take place. The possibility of endothermic reactions seems to be a more open question.

mations by batholithic magmas consists in emphasizing the obvious fact that the average xenolith and average wall-rock of batholiths do not show direct evidence of melting or of solution in the granitic magma. This objection has been answered by the writer in several publications* and also by Andrews in most vivid fashion.† The point has, however, been restated by several authorities without any adequate discussion of the subject. No one can deny that, when the magma is all but frozen, it is incapable of assimilating xenolith or wall-rock on any large scale. The practical question is as to the magma's efficiency during the long antecedent period of its history. It is true that bed-ridden centenarians did not build the pyramid of Cheops; it does not follow that men did not build it.

If it be assumed that the quartz of granite has crystallized at or below 800° C.,‡ it follows that complete rigidity is not established in a granite batholith until it has cooled to at least 800° C. Down to about that temperature limit (of undercooling), therefore, magmatic stoping is still possible. The lowest limit of active assimilation cannot well be much below 1000° C., while the temperature required to melt the average xenolith is about 1200° C. As the viscosity of granitic magmas increases greatly below 1200° C., diffusion and convection must become rapidly inadequate to remove syntectic films at main contacts, so that the molecular lowering of the fusion-point will be confined, within the interval 1200°–800° C., chiefly to the sunken blocks. It follows, first, that in the very long period of time occupied in the cooling of a plutonic mass from 1200° C. to 800° C., there will be little or no melting or solution of wall-rock; secondly, that many shells of roof-rock, perhaps aggregating thousands of feet in thickness, may be stoped away during that same period of time. In other words, because the shatter-period is longer than the period of active assimilation at the roof, it is an essential feature of the stoping hypothesis that neither visible xenolith nor main wall of a granite batholith should normally show a collar of assimilation. So far from being a difficulty, the fact that this is generally true is a distinct argument in favor of the stoping hypothesis.

Abyssal assimilation.—In the first paper of this series the writer stated grounds on which one must believe in the complete solution of engulfed xenoliths. One has only to imagine a block of gneiss, say ten meters in diameter, sinking through a column of superheated basalt twenty or thirty kilometers

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* This Journal, xv, p. 281, 1903; Bull. Geol. Soc. of America, xvii, p. 372, 1906.

† Records, Geol. Surv. of N. S. Wales, viii, Pt. 1, p. 126, 1905.

‡ Cf. A. L. Day and E. S. Shepherd, Jour. Amer Chem. Soc., xxviii, p. 1099, 1906.

deep, to become convinced of the ultimate fate of that block. If the somewhat cooled lavas described by Lacroix,* von John,† Dannenberg,‡ Sandberger§ and others could dissolve rock-inclusions in the notable way described by those authors, we must credit a vast solutional efficiency to plutonic magma when it attacks similar blocks in great depth. The lava has a few hours or days in which to do its work ; the abyssal magma has centuries if not a large part of a geological period!

It must be remembered that geosynclinal sediments are rocks unusually rich in water, chlorides, sulphur trioxide, etc.; all substances aiding solution in the primary magma and in the secondary (syntectic) magma itself. It is probably also owing to these fluids in large part that granitic magmas have crystallized at comparatively low temperatures.

The conception of stoping with abyssal assimilation has many more points in its favor than can be cited for pure marginal assimilation. A few of the special grounds for preferring the newer to the older hypothesis may be noted.

First, marginal assimilation is largely effective only in the earliest part of the magma's history, when it is absolutely and relatively very hot. There is thus an early time-limit fixed for the gigantic work of dissolving the thousands of cubic kilometers actually replaced in the intrusion of a large batholith.

Secondly, the assimilation, on the older view, takes place primarily on main contacts and along a relatively limited amount of surface. For example, a cube of wall-rock one kilometer in diameter can offer only about 1,000,000 square meters of surface at a time to the dissolving magma. If that same cube were shattered into cubes 10 meters on the side and then engulfed, the magma would carry on the work of solution on 600,000,000 square meters of surface.

Thirdly, the average crust-rock being allied chemically to gneiss, is more soluble in basic magma than in acid. On the stoping hypothesis, solution of the xenolith generally occurs in the lower, basic part of the magmatic chamber; on the older view, it is granitic magma which must do most of the work of solution. For even if the originally injected magma is a basalt, the products of its assimilating activity, being more acid and less dense than itself, must remain at the batholithic roof and rapidly assume the chemical composition of mean mountain-rock. It follows that the primary magma must be enormously more superheated than is required on the stoping hypothesis or than seems easy of explanation, in view of the

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* Les Enclaves des Roches Volcaniques, Macon, 1893.

† Jahrb. d. k. k. Reichsanstalt, Vienna, lii, p. 141, 1902.

‡ Tscherm. Min. u. Petrogr. Mitth., xiv, p. 17, 1895.

§ Sitzungsber. K. Bair. Akad. Wiss., p. 172, 1872.

difficulty of understanding how plutonic magma, which is capable of intrusion, can become superheated more than two or three hundred degrees Centigrade.

Fourthly, the stoping hypothesis has the special advantage of providing a mechanism of thorough agitation within a batholith. Strong stirring of the mass is induced by the sinking of xenoliths and by the necessary rising of the magma locally acidified by their solution. This agitation can explain the marvelous homogeneity in each large batholith. It helps greatly to explain the manifest evidences of magmatic differentiation within batholiths—splittings and segregations that cannot be due to the slow process of molecular diffusion or to mere thermal convection. The whole process of stoping and the rising of syntectic magma tends to equalize the temperatures in the batholithic chamber and thereby we can understand the even grain and rapid, nearly simultaneous crystallization of a batholith throughout its visible depth.

Fifthly, the engulfment of blocks of geosynclinal sediments enriches all parts of the batholiths with water, chlorides, etc. which so greatly aid solution ; while, on the older view, these agents are confined to the uppermost part of the chamber.

Sixthly, as already noted, the cleansing of syntectic films from contact of solid and liquid is much the more rapid and perfect according to the stoping hypothesis, thus providing and renewing conditions for molecular lowering of the fusion-point along contacts.

In short, the newer view has the advantage of not only better explaining the facts of the field but it is incomparably more economical of the heat postulated for the work of batholithic replacement than is the theory of pure marginal assimilation. Melting and marginal assimilation of country-rock takes place in the initial, superheated condition of a basaltic injection, but must be regarded as always subordinate in replacement efficiency to stoping and abyssal assimilation.

Existence of basic stocks and batholiths.—Finally, the fact that some large bodies of plutonic rocks are basic has been advanced as an objection against the idea of stoping.* This fact early impressed itself on the present writer and led to his reviewing the geological literature to determine, if possible, the number, distribution, and age of these bodies. It was found that most of those which have undoubtedly batholithic development on a large scale are of pre-Cambrian age and are chiefly anorthosite intrusions. In this Journal, vol. xx, 1905, p. 216, the guarded suggestion was made that the anorthosites of Canada and the Adirondack Mountains are so basic because of the absorption of crystalline limestones. On more

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* W. Cross in Science, xxv, p. 620, 1907.

mature consideration this suggestion seems inadequate and a more general explanation must be sought.

Adams describes the great anorthosite mass of Morin, Quebec, as genetically associated with an adjacent gabbro body of batholithic size.* The one is either a differentiate from the other or both are expressions of a common basic magma. The latter seems the more probable relation. In fact, both batholiths appear to represent the crystallized products of a magma allied to, if not identical with, the primary basaltic magma which has been the source of the heat in post-Archean batholithic intrusions.

The conditions of intrusion for these "upper Laurentian" masses seem to have differed from those typically represented in the post-Cambrian batholiths. The latter have been developed under heavy geosynclinal covers which have entailed considerable superheat in the basaltic substratum. It is not impossible that the "upper Laurentian" basic magmas, already cooled nearly to the solidification-point, were injected into the then thinner crust, or warped up with it, during crustal disturbance. Lacking superheat these magmas lacked stoping and assimilating power and, consequently, did not become acidified.

In favor of the conception that these magmas were near the solidification point at the time of their intrusion, is the fact that the anorthosites often show primary banding and are most extraordinarily granulated, as if by dynamic force which acted on the congealing mass near the close of the intrusion-period. Concerning the granulation Adams writes: "There are no lines of shearing with accompanying chemical changes, but a breaking up of the constituents throughout the whole mass, though in some places this has progressed much further than in others, unaccompanied by any alteration of augite or hypersthene to hornblende, or of plagioclase to saussurite; these minerals though prone to such alteration under pressure remaining quite unaltered, suffering merely a granulation with the arrangement of the granulated material in parallel strings. This process can be observed in all its stages, and there is reason to believe that it has been brought about by pressure acting on rocks when they were deeply buried and very hot. The anorthosite areas, of which there are about a dozen of great extent with many of smaller size, are distributed along the south and southeastern edge of the main Archean protaxis from Labrador to Lake Champlain, occupying in this way a position similar to that of volcanoes along the edge of our present continent." †

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* Canadian Record of Science, 1894–5.

† F. D. Adams, Jour. of Geol., i, p. 334, 1893.

Cushing and Kemp have published somewhat detailed accounts of the anorthosite forming a post-Grenville and pre-Cambrian batholith and its satellitic stocks in New York state.* The batholith covers about 3000 square kilometers in area. Cushing's petrographical descriptions show many points of agreement with Adams's description of the yet vaster Canadian batholiths. The anorthosite generally crystallized with exceptionally coarse grain and a porphyritic structure. Intense granulation is here again the rule, and from Cushing's published data it seems probable that the granulation followed hard after the act of intrusion. The characteristics and field-relations of the anorthosite are such as to suggest that they have resulted from abyssal injections of magma which was not superheated. A limited amount of stoping is possible in such a magma but extensive assimilation of country-rock is not possible for that magma.

Kemp has suggested that the New York anorthosite has, through fractional crystallization and the settlement of the basic minerals of early generation, been derived from a normal gabbro. † This idea may possibly explain the existence of the more pyroxenic contact-phase regularly occurring in the batholith. The contact rock is either gabbro or anorthosite-gabbro. It may represent the original magma but little affected by the settlement of the crystals of iron-ore, pyroxene and olivine. In the more slowly cooled interior of the mass their settlement could take place on a large scale.‡ In the Canadian batholiths this differentiation by fractional crystallization may have occurred just before the huge masses were injected into the crust.

The problem of the anorthosites is clearly as yet one for speculation rather than one capable of final solution. It seems proper to believe, however, that, since all or nearly all of the known anorthosite and gabbroid batholiths are of pre-Cambrian age, they owe their origin to special pre-Cambrian conditions. The stoping hypothesis as a whole expressly relates only to conditions which have characterized orogenic belts in post-Archean time.

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*H. P. Cushing, 18th Report of the State Geologist. Albany, p. 101, 1900; New York State Museum Bulletin No. 95, p. 305, 1905, and Bull. 115, p. 471, 1907. J. F. Kemp, 19th Ann. Report, U. S. Geol. Surv. pt. 3, p. 409, 1899.

† Op. cit., p. 417.

‡ Incidentally it may be remarked that the same conception might conceivably explain many internal basic contact-phases occurring in acid stocks and batholiths. This explanation is evidently opposed in principle to the prevailing view that the basic contact-shells are due either to diffusion of basic molecules toward cooling-surfaces, or to the combined influence of fractional crystallization and convection-currents in the magma. Neither of these hypotheses seems acceptable in the case of the anorthosite-gabbro batholiths, and the writer has come to question their validity as final explanations for some other types of intrusive bodies.

The gabbros of Paleozoic or later age represent bodies either too small or of too low temperature to carry on extensive stoping before their magmas became rigid. Diorite stocks and batholiths, according to the hypothesis, represent undifferentiated or but partially differentiated syntectic magma—of composition intermediate between rhyolite or granite and basalt. The average chemical analyses of the world's basalt, granite and diorite have been calculated by the writer from Osann's compilation.* It has been found that the diorite analysis is, oxide for oxide, almost the exact mean between the other two analyses.

These various considerations incline the writer to the view that the existence of a few large basic intrusions, cutting acid rocks, is not necessarily a fact fatal to the stoping hypothesis. Each of the cases needs special study, for they may shed much light on the difficult plutonic problem.

Differentiation of the syntectic magma.—In order to trace further the history of the engulfed xenoliths several principal conditions must be recognized. If the invading magma is superheated, so as to have the temperature of 1300° C., a block of heavy gneiss (sp. gr. at 20° C., 2·85) will speedily be heated to and above its own melting-point. While some of it is dissolved, much of it is converted into a molten globule of essentially pure gneiss. From Table II we see that the specific gravity of the globule would be about 2·40, while that of the surrounding primary magma would average about 2·72. This difference of density means that the globule must rise through the primary magma with a speed even greater than that with which the solid rock (specific gravity about 2·75) formerly sank.† As it rises the globule would wholly or partly mix with the primary magma. If wholly mixed the primary magma rapidly becomes a syntectic magma, approaching a diorite in composition. The molecular, syntectic film which is formed by solution along the surfaces of the block must, theoretically, contain equal parts of primary magma and xenolith material. If the former be basalt and the latter a granitoid gneiss, the film must have a dioritic composition. All three kinds of secondary magma—molten globules of gneiss, globule-material dissolved in primary magma as the globule rises, and the material formed in the molecular, syntectic film—must be considerably less dense than the primary basalt and rise toward the top of the batholith chamber. A net result of abyssal assimilation is a compound, secondary magma either dioritic or more acid than diorite.

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* Beiträge zur Chemischen Petrographie, II Teil; Stuttgart, 1905.

† The same reasoning applies to xenoliths of normal gneiss immersed in acidified gabbro or diorite magma.

This reasoning is deductive but it can in some measure be checked by actual observations. Lacroix describes blocks of gneiss up to a cubic meter in size, which have been immersed in molten basalt. By the heat of the lava the blocks have been "entirely transformed" into porous glass.* Von John has described other examples of the same transformation.† The present writer has correlated a considerable number of instances where the gravitative stratification has certainly been produced in thick intrusive sheets.‡

A number of observers have come to the conclusion that the very act of the assimilation of acid material by basalt predisposes the magma to magmatic splitting. The fullest statement of this view is given by Loewinson-Lessing, in his remarkable "Studien über die Eruptivgesteine."§ There appears to be, as it were, a steady "antagonism" between the ferromagnesian and acid-alkaline elements in magmas. This primordial tendency toward immiscibility may well explain the dominant acidity and alkalinity of the pre-Cambrian terranes in every continent. From the earliest times the granito-rhyolite magma has tended to separate from the basaltic wherever the viscosity has been sufficiently low for such splitting. For similar reasons it appears that the syntectic magma of post-Archean batholiths only reaches a stable condition when it assumes the ancient relation. In the average case the fluidity has been high enough for the splitting. In some cases, however, it was so low that the undifferentiated syntectic has crystallized as diorite and allied rocks.

When the syntectic has differentiated, the process must be primarily controlled by density, so that the acid, generally granitic, product rises to the top of the chamber. There it may become locally further differentiated through fractional crystallization or other relatively subordinate process.

Without discussing the causes of differentiation in more detail, it suffices to point out, in summary, that magmatic stoping involves the placing of gravity at the head of the list of forces which produce the actual diversity among igneous rocks. In this the stoping hypothesis is believed to match the facts observed in experimental, industrial and geological studies of silicate melts.

Origin of granite; the petrogenic cycle.—The stoping hypothesis involves a more or less definite corollary relating

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* Les Enclaves des Roches Volcaniques, p. 563-5; Macon, 1892.

† Op. cit., p. 141.

‡ This Journal, xx, p. 185, 1905; also Festchrift zum siebzigsten Geburtstage von H. Rosenbusch, p. 203, Stuttgart, 1906.

§ Comptes Rendus, Congrès géol. internat, VII^e session, St. Petersburg, p. 375, 1899.

to the genesis of granite as the staple visible material of post-Archean batholiths. Erosion has nowhere penetrated more than a few thousand meters in any of these batholiths. Considering the scale of operations, it follows that practically all post-Archean batholithic rock is of secondary origin. The field-relations show that the granite often replaces much geosynclinal sediment. Thick as many geosynclinal prisms are, however, it seems clear that another large, perhaps the larger, part of the replaced rock may be pre-Cambrian crystalline materials (averaging granitoid gneiss in chemical composition) which underlie geosynclinal areas, as they apparently underlie all the continental areas. The similarity of granites throughout the world may, indeed, be explained by the uniformity of the earth's primordial, acid shell and by the relative uniformity in average chemical composition of the greater geosynclinal prisms. Where sediments only are assimilated, the secondary granite may be of abnormal composition; this is the case with the granite of the Moyie Sill.*

The longer an abyssally injected and assimilating body holds its fluidity, the more perfect should be the gravitative differentiation. During this active stage lateral fissures or laccolithic spaces may be filled with offshoots of the slowly changing magma. In general these satellitic injections should succeed each other in the order of increasing acidity. In a fully represented petrogenic cycle at a batholithic area, then, the oldest intrusion should be a rock of gabbroid (basaltic) composition and the youngest an acid granite (chemically a rhyolite or quartz porphyry). Between these two an indefinite number of intermediate rock-types varying according to their degree and kind of differentiation from the syntectic—itself continuously varying in composition—might be represented in dikes or other satellitic forms. This further deduction from our hypothesis seems to be fairly matched by the observed order of igneous intrusions about the world's batholiths.†

Again, successive batholithic intrusions in the same area should show the same law of increasing acidity with decreasing age. If, for example, a crystallized granodiorite batholith be itself attacked by a later abyssal intrusive and in large part stoped away and remelted, the secondary magma collecting at the roof of the later batholith should be more acid than granodiorite. This would be expected because the mere act of remelting entails further gravitative differentiation. Each time that a silicate mass passes through the optimum temperature for magmatic splitting—probably an interval of one or

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* This Journal, xx, p. 196, 1905.

† See first intrusion paper, p. 292.

two hundred degrees above its melting point*—the separation of its acid-alkaline and ferromagnesian elements by gravity is further perfected. Morozewicz has given a telling experimental demonstration of the process. He melted two pounds of granite and left the superheated melt in a hot part of an active glass-furnace for five days. It was then cooled to a glass. At the end of the time he found that the lower part of the melt carried 59·20 per cent of silica, the upper part 73·65 per cent; the original granite showed 68·9 per cent.† An actual case of repeated differentiation of the kind seems to be represented in the Okanagan Mountain range, where, one after another, the Osoyoos-Remmel, Similkameen and Cathedral batholiths have been intruded, and clearly in the order of decreasing specific gravity of the rocks.‡

It is, however, to be expected, on the stoping hypothesis, that the primary basaltic magma may close an entire petrogenic cycle, since the latest phase of a batholith, after crystallizing, may be fissured and injected with a small volume of the substratum. The common occurrence of diabase or prophyrite dikes in granite may be thus explained.

Origin of magmatic water and gases.—Finally, the stoping hypothesis implies that, since post-Archean batholiths have generally replaced large volumes of sediments, the volatile matter which is normally trapped within a geosynclinal prism should form an important part of the secondary magma.

An approximate idea of the amount of volatile matter in the average argillite§, sandstone and limestone of the world is readily obtained. For this purpose we may use Clarke's composite analyses of 843 limestones, 624 sandstones, 27 Mesozoic and Cenozoic shales and of 51 Paleozoic shales, together with 38 analyses of various argillites from different parts of the United States.‖ From these analyses the writer has determined, for the argillites, the average amount of water below 110° C. (H_2O-), water above 110° C. (H_2O+), carbon dioxide, carbon (and carbonaceous matter), and sulphur (in SO_3). These averages represent, respectively, 116, 116, 106, 78 and 78 typical specimens of argillite from as many localities. The averages for sandstone and limestone have been taken directly from Clarke's work and all three sets are noted in the following table:

An inspection of the table makes it clear that the total of the "combined water", carbon dioxide, carbon and carbonaceous matter, sulphur and chlorine in the stratified rocks

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* F. Loewinson-Lessing, op. cit., p. 380.

† Op. cit., p. 232. Cf. C. Doelter, Petrogenesis, Braunschweig, p. 79, 1906.

‡ Bull. Geol. Soc. America, xvii, p. 329, 1906.

§ The term "argillite" here includes both shales and slates.

‖ F. W. Clarke, Bull. No. 228, U. S. Geol. Surv., p. 20 ff., 1904.

TABLE IV.

	843 limestones	624 sandstones	116 argillites
H_2O-	·26%	·29%	1·25%
H_2O+	·73*	1·41	3·71
CO_2	38·03	2·64	2·45
C (including carbonaceous matter)	?	?	·81
S	·11	·03	·25
Cl	·01	trace	trace
Total	39·14	4·37	8·47

exposed in any geosynclinal prism must represent at least six per cent of the whole mass. It is highly probable that this minimum amount of volatile matter has similarly characterized such a series ever since the period in which the series was deposited.

No petrographer needs to be reminded that none of the commoner types of igneous rock contains anything like six per cent of original volatile matter. Nevertheless it is instructive to survey the facts actually visible in quantitative analyses of the igneous rocks. Water is the only volatile substance determined in igneous-rock analyses often enough to afford nearly reliable world-averages. From Osann's compilation the writer has deduced the average of H_2O- and H_2O+ for each of the following groups: 48 granites, 47 diorites, 12 gabbros, 24 basalts, 5 augite andesites and 11 rhyolites (Table V).

TABLE V.

	H_2O-	H_2O+
Granite	·17%	·64%
Diorite	·19	1·20
Gabbro	·26	1·35
Basalt	·73	1·03
Augite-andesite	·40	1·48
Rhyolite	·30	1·23

Clarke's averages for the volatile substances occurring in igneous rocks which have been analyzed according to approved methods are:

H_2O-	·40%
H_2O+	1·46
CO_2	·52
S	·11
Cl	·07
F	·02

Much of the combined water, probably all of the hygroscopic water, and most of the carbon dioxide of these analyzed igneous rocks are due to alteration or to absorption at the earth's surface. Allowing for that fact, it seems probable that none of the more widely distributed igneous rocks carries much more

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* Includes organic matter.

than one per cent of its own weight in volatile matter directly derived from the earth's interior.

It follows that an enormous amount of water, carbon dioxide and carbon and sulphur compounds may be given off each time that geosynclinal sediments have been assimilated by molten and then crystallized magma. From each cubic kilometer of assimilated sediments about six per cent by weight of liquids and gases must be dissolved in the syntectic magma and, as crystallization proceeds, a large part of this fluid must be expelled.

In less important degree we may expect that the remelting or solution of an igneous rock by an intrusive magma should cause the evolution of some of the fluid matter which had been, as it were, frozen into the solid rock. Lincoln has aptly called such fluids "repressed emanations."* Gautier's and Brun's experiments show that many and probably all igneous rocks give off gases on being highly heated.† Reheating after cooling causes the renewed emanation of gases. Volatile matter trapped in crystallized secondary granite may thus be driven off, if that granite be dissolved in a younger molten magma with subsequent crystallization of the syntectic.

The stoping hypothesis in its broadest statement demands, therefore, that post-Archean, batholithic granites, syenites and diorites should be accompanied by special evidences of fluid emanations.

These fluids were deposited and buried in the strata. They have been resurrected in their activity. They have "risen again", both literally and figuratively; they may be called "resurgent" emanations. The "repressed" emanations of secondary igneous rocks may similarly be liberated by the distilling action of younger magma; as these fluids become revivified in their geological activities they may be regarded as forming a second kind of "resurgent" emanations. All "resurgent" emanations are of secondary origin and, therefore, stand in contrast to "juvenile" emanations, namely, those which, for the first time, have issued from the earth's interior and become geologically active on or near the surface. Magmatic emanations are, apparently, divisible into two great classes, both of which should be recognized in complete discussions of ore-deposits.

That the stoping hypothesis stands this further test seems to the writer entirely clear. The prevalence of quartz veins and pegmatites in the walls and roofs of actual granitic, syenitic, and dioritic stocks and batholiths, and the intensity of the contact-metamorphism produced by the intrusions of, and especially the emanations from, these rocks are facts as famil-

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*F. C. Lincoln, Economic Geology, ii, p. 268, 1907.

†A. Brun, Archives des Sciences Phys. et nat. Geneva, May and June, 1905 and November, 1906; A. Gautier, Annales des Mines (6), ix, p. 316, 1906, and Econ. Geol., i, p. 688, 1906.

iar as the comparative rarity of quartz-veins and pegmatites about gabbroid masses and the comparative feebleness of the contact-metamorphism produced by gabbros. The abundant water found in obsidian and rhyolite is, in this view, largely or wholly of secondary origin. Volcanic gases may similarly be largely "resurgent" rather than "juvenile." In no case, however, would one class of emanations be represented to the exclusion of the other. For post-Archean granites the emanations are dominantly "resurgent"; for gabbros the emanations are largely or dominantly "juvenile."

Conclusion.—The first two papers of this series were written in the light of experimental results bearing on the methods of igneous intrusion. Since 1903 a number of additional leading experiments according to refined methods have been carried out by Doelter and his colleagues, by the Geophysical Laboratory staff at Washington, by Brun, Gautier, Hall, Douglas, Ladenburg and others. These later investigations, like those of Deville, Bischof, A. Becker, Lehmann, Fouqué, Michel Lévy, Cossa, Thoulet, Barus, Oetling, Hofman, Tammann, Morozewicz, Forbes, Joly, Mallet, Reade, Cusack, Weber, Åkerman, Vogt, Bartoli, Jamin, Lagorio, and others, seem to show that the physical conditions and processes involved in the stoping hypothesis have been in the main correctly stated.

It is obvious that further laboratory study of rocks on the physico-chemical side is highly desirable, but the accordance of independent experimental results now on record appears to have demonstrated: first, the enormous efficiency of thermal expansion in causing shattering stresses in solid rock; secondly, the fact that the average xenolith must sink in molten granite, syenite, diorite and acid gabbro when these magmas are under ordinary plutonic conditions; thirdly, that the sunken xenoliths must melt or become dissolved in the depths of plutonic magma, forming syntectic magma; and fourthly, that, if the primary magma is basic, the average syntectic must rise through it and thus collect at the top of the magmatic chamber.

The attempt has been made, in using the experimental results of Barus, Roberts-Austen and Rücker, Weber, Bartoli, Åkerman and Vogt, to estimate the amount of average crust-rock (gneiss) which may be dissolved in one volume of superheated primary magma (basalt). The sources of superheat in plutonic magma and a rough quantitative analysis of abyssal assimilation have been discussed. The result points to an explanation of the fact that magmatic stoping has not destroyed the roofs of post-Archean batholiths. The more general problem of the stability of batholithic covers which, on any theory of magmatic intrusion, seem to be in danger of foundering in the less dense magmas, is seen to have become less serious as that problem is viewed in the light of the new estimates of magmatic density. The possibility that some of the Archean batholiths were the scenes of actual, partial foundering of the earth's crust had been noted; the suggestion is made that, in late pre-Cambrian time, it had become thick and strong enough to inhibit extensive foundering of batholithic covers.

Various objections to the hypothesis seem to fall away so soon as they are confronted by the facts of experimental investigation on melted rocks and silicate mixtures. Other objections have been met by the facts derived from the field-work of many observers. The facts of field-occurrence and field-relations are opposed to the "laccolithic theory" and to that of marginal assimilation; on the other hand, these facts all seem to be explicable on the stoping hypothesis, which, therefore, is taken by the writer to afford the best working basis for the future investigation of granitic batholiths. In this conclusion the writer is in full agreement with Andrews and Barrell, two authorities who, with the intrusion-problem expressly in mind, have carefully scrutinized actual batholiths.

The hypothesis involves several important consequences, a few of which have been considered. If magmatic stoping and abyssal assimilation have largely operated during the intrusion of post-Archean batholiths and stocks, it follows that the material of these bodies is largely or wholly of secondary origin. In each case it is a differentiate from a syntectic magma formed by the solution of primary (acid) crust-rock or of geosynclinal sediments in the (probably basic) magma of the substratum. The order of eruption in batholithic areas, with respect to the acidity of the rocks, need not be absolutely fixed, but should show a strong tendency toward the succession of eruptives becoming more acid with decreasing age. Lastly, since most post-Archean granites have replaced large volumes of sedimentary rock, the suggestion seems warranted that the water and other volatile matters regularly given off in great volume from granitic magma, are also of secondary origin. Geosynclinal sediments are normally charged with relatively abundant fluids; it seems inevitable that these should, in part at least, be given off during the solution of wall-rock or engulfed xenoliths in an invading magma.

The principal field-relation on which the foregoing discussion hangs is the "replacement" of country-rock by magma in the intrusion of stock or batholith. Slow digestion and solution on main contacts has caused the replacement to a limited degree, but the facts of nature seem to enforce belief in the more rapid and more important mechanical replacement through magmatic stoping.