A REVIEW OF THE EXISTING HYPOTHESES ON THE ORIGIN OF THE SECONDARY SILICATE ZONES AT THE CONTACTS OF INTRUSIVES WITH LIMESTONES.

PART II.¹ PHYSICS AND CHEMISTRY OF THE CONTACT ZONES AND CONCLUSIONS.

W. L. UGLOW.

III.

COMPARISON OF ANALYSES OF FRESH AND ALTERED LIMESTONES BY MEANS OF THE COMPOSITE STRAIGHT-LINE DIAGRAM.

It is a very difficult matter to make a correct statement offhand as to whether or not a bed of limestone contains impurities enough and in the right proportions to afford lime-alumina and other silicates on recrystallization. Even a chemical analysis of a typical specimen of the fresh limestone is by no means a sufficient foundation on which to base such a statement. Only careful sampling of the fresh and altered rocks, and a comparison of their compositions on a rational basis of comparable samples, can show whether or not the "secondary silicate zone" may be merely the result of redistribution and recrystallization of the original constituents of the limestone.

In very few cases, indeed, has this method been followed. The only fruitful sources of information with regard to specific contact-zones are papers and reports dealing with western mining camps. A great deal of the field work was undertaken by consulting geologists and geologists from the United States Geological Survey; and the problem of the origin of the "secondary silicate zones" was necessarily relegated to the position of a side-issue. The amount of investigation and sampling required to reap many useful results in this regard could not be devoted to

¹ Part I. of this article appeared in ECONOMIC GEOLOGY, Vol. VIII., No. 1. pp. 19-50.

that particular phase, and hence the conclusions of these geologists may not have been based on all the pertinent data.

The authors of the U. S. G. S. publications referred to, especially those dealing with the western camps, have been too prone to state that the limestone beds now "replaced" by silicates were too pure originally to afford these results of themselves. Careful reading of their own discussions of the stratigraphic column will show that even in the very horizon of the ore bodies, the limestone is not pure calcium carbonate.¹ In the very nature of the case, it is difficult to conceive of beds of limestone of any thickness, absolutely free of chert, sand, or clay, to say nothing of iron oxide, and the carbonates of iron and magnesium. In most of the contact camps the limestones are interbedded with sandstones, quartzites, shales, graywackes, dolomites, etc., and in several cases there are all gradations between them.

In making a comparison of the chemical compositions of the unaltered and metamorphosed rocks, it is of the first importance to remember that *average* samples should be compared with each other. The "secondary silicate zone" in nearly all cases is composed of three or more minerals—garnet, epidote, tremolite, quartz, calcite, etc. A comparison of one or two samples of the mineral garnet with one or two samples of a pure limestone, not from the same horizon, such as Kemp² has made, gives results of little value. Lindgren,³ again, states that the andradite garnets of the contact-zones in the Clifton-Morenci camp contain more iron than could be derived from the limestone. His conclusion is invalidated because comparable average samples should alone be used. It is the average chemical composition of the rock of the "secondary silicate zone" and not of one mineral, that should be compared with that of the sedimentary series of the same horizon. Such minerals and phases of metamorphism as are produced during the second or metasomatic stage of contact action should of

¹ Kemp and Gunther, *A. I. M. E.*, XXXVIII., p. 276; F. L. Ransome, Prof. Pap. 21, p. 55; W. Lindgren, Prof. Pap. 43, p. 71.

² J. F. Kemp, "Ore Deposits at the Contacts of Intrusive Rocks and Limestones," *ECON. GEOL.*, Vol. II., No. 1, p. 1, 1907.

³ W. Lindgren, U. S. G. S., Prof. Pap. 43.

course be eliminated from the sample which represents the average altered rock to be used in comparison with the fresh rock. Too much care cannot be exercised in the selection of samples, and the averages in each case should be weighted ones.

A. IRON SPRINGS, UTAH.

	No. 1.	No. 2.	No. 3.
SiO ₂	8.08	52.00	15.5
Al ₂ O ₃	1.95	9.32	20.9
Fe.....	0.66	5.43	12.1
MgO.....	2.86	9.40	30.4
CaO.....	46.67	14.47	322.0
Na ₂ O.....	0.13	1.94	6.7
K ₂ O.....	0.77	1.41	54.5
H ₂ O+.....	1.01	3.30	30.6
CO ₂	37.60	0.63	5,975.0

No. 1 = Unaltered blue limestone.

No. 2 = Altered limestone near andesite intrusive.

$$\text{No. 3} = \frac{\text{No. 1}}{\text{No. 2}} \times 100.$$

Reference: Bull. U. S. G. S., 338, pp. 26-27.

B. HASTINGS COUNTY, ONTARIO.

	No. 1.	No. 2.	No. 3.
SiO ₂	33.02	51.75	63.8
Al ₂ O ₃	9.08	18.98	47.9
Fe.....	3.25	6.78	47.9
MgO.....	4.20	4.98	84.4
CaO.....	31.02	7.63	406.8
Na ₂ O.....	1.17	4.30	27.2
K ₂ O.....	0.85	1.86	45.7
H ₂ O+.....	1.08	1.42	76.1
CO ₂	15.27	0.11	13,890.0

No. 1 represents the first stage of alteration from a limestone. Recalculation of No. 1 (a) (Adams) after eliminating TiO₂.

No. 2 = Altered (amphibolite). Recalculation of No. 3 (Adams) after eliminating TiO₂, S, MnO, Cl.

$$\text{No. 3} = \frac{\text{No. 1}}{\text{No. 2}} \times 100.$$

Reference: F. D. Adams, *Jour. Geol.*, XVII., No. 1, 1909.

After a somewhat diligent search of the literature, and through the kindness of W. J. Mead, of the department of geology of the

University of Wisconsin, analyses of fresh and altered limestones were obtained from the following camps: Iron Springs, Utah; Hastings County, Ontario; Bingham, Utah; Bisbee, Arizona; White Knob, Mackay, Idaho; Chanacillo, Chile; San Jose, Tamaulipas, Mexico; Clifton-Morenci, Arizona. In all cases but the first two the analyses are incomplete; and without any exception, they are not based on average samples. Nevertheless, they afford the best available quantitative data, and as such they may give some valuable suggestions. Averages were struck by the writer from the analyses where it seemed advisable, and the respective quotients were platted on the composite straight-line diagram on page 219 (Fig. 12).

C. BINGHAM, UTAH.

	No. 1.	No. 2.	No. 3.
SiO ₂	12.50	50.41	24.8
Al ₂ O ₃ }	1.99	0.80 ¹	(249.0)
Fe ₂ O ₃ }			
MgO.....	3.66	24.57	14.9
CaO.....	48.34	9.74	483.0
H ₂ O+.....	4.31	11.81	36.5
CO ₂	28.06	1.61	1,740.0

No. 1 = Fresh gray limestone (Old Jordan mine).

No. 2 = Altered limestone (white marble with little tremolite).

No. 3 = $\frac{\text{No. 1}}{\text{No. 2}} \times 100$.

Reference: U. S. G. S., Prof. Pap. 38, p. 191.

Figure 12 is constructed in accordance with a method used in the metamorphic laboratory of the University of Wisconsin, and described by W. J. Mead² in a recent number of ECONOMIC GEOLOGY. It is simply a convenient graphic method of representing the changes in chemical composition which a rock undergoes during alteration. The division of the percentages of the constituents in the fresh rock by the percentages of the respective constituents in the altered rock gives a series of ratios which show at a glance how the different oxides have acted with respect to each other. Although the analyses themselves might be

¹ Only very approximate. Spoils value of quotient. (Not platted.)

² W. J. Mead, "Some Geologic Short-Cuts," ECON. GEOL., VII., No. 2, 1912, pp. 143-144.

FIG. 12. Composite straight-line diagram, A, Iron Springs, Utah; B, Hastings-Grenville, Ont.; C, Bingham, Utah; D, Bisbee, Arizona; E, White Knob, Idaho; F, Chanacillo, Chile; G, San Jose, Mexico; H, Clifton-Morenci, Ariz.

greatly improved upon, the platting shows without doubt certain very significant tendencies at work, during the contact metamorphism:

D. BISBEE, ARIZONA.

	No. 1.	No. 2.	No. 3.
SiO ₂	2.52	28.55	8.8
Al ₂ O ₃ }	0.24	2.16	11.1
Fe ₂ O ₃ }			
MgO.....	0.76	13.62	5.6
CaO.....	53.68	26.20	205.0
H ₂ O+ }		3.08	
CO ₂ }	43.07 ¹	19.00	227.0
FeS ₂ }		5.63	

No. 1 = Unaltered Naco limestone (III., p. 148).

No. 2 = Altered limestone (I., p. 148).

$$\text{No. 3} = \frac{\text{No. 1}}{\text{No. 2}} \times 100.$$

Reference: U. S. G. S., Prof. Pap. 21, p. 148.

E. WHITE KNOB, IDAHO.

	No. 1.	No. 2.	No. 3.
SiO ₂	8.07	37.43	21.5
Al ₂ O ₃ }	2.34	29.08	8.0
Fe ₂ O ₃ }			
MgO.....	2.44	0.44	555.0
CaO.....	47.23	32.67	144.2
CO ₂	39.72	—	α

No. 1 = Unaltered limestone (average of Nos. 1 and 2, bottom of p. 6).

No. 2 = Altered limestone (average of Nos. 4 and 5, p. 7).

$$\text{No. 3} = \frac{\text{No. 1}}{\text{No. 2}} \times 100.$$

Reference: J. F. Kemp, ECON. GEOL., II., p. 6, 1907.

Note.—These analyses are not comparable.

(a) The slope of the lines joining corresponding points on the SiO₂, Al₂O₃ and iron lines is in every case very slight, and approaches perpendicularity. In accordance with the method of interpretation used in the article referred to, this indicates that the ratio of SiO₂:Al₂O₃:Fe (or SiO₂:Al₂O₃+Fe₂O₃) in the unaltered rock is very nearly identical with their ratio in the altered type.

¹ Enough CO₂ added to partial analysis to change MgO and CaO to carbonates.

F. CHANACILLO, CHILE.

	No. 1.	No. 2.	No. 3.	
SiO ₂	22.82	47.97	47.6	No. 1 = Unaltered limestone.
Al ₂ O ₃ } Fe ₂ O ₃ } ..	3.53	10.12	34.9	No. 2 = Altered limestone.
MgO	11.46	16.71	68.5	No. 3 = $\frac{\text{No. 1}}{\text{No. 2}} \times 100$
CaO	29.73	9.65	308.0	
Na ₂ O } K ₂ O } ...	1.69	1.27	133.0	
CO ₂	31.09	11.64	274.0	

Reference: Natur Marburg, 1870, p. 26.

G. SAN JOSE, MEXICO.

	No. 1.	No. 2.	No. 3.	
SiO ₂	4.67	9.55	48.9	No. 1 = Fresh limestone (average of (1) and (2), Kemp).
Al ₂ O ₃ } ..	0.65	1.28	50.8	
Fe ₂ O ₃ }				
MgO.....	0.44	0.43	102.0	No. 2 = Crystalline limestone (analysis No. 3, Kemp.)
CaO.....	52.70	49.79	101.0	
CO ₂	41.98	39.61	105.9	No. 3 = $\frac{\text{No. 1}}{\text{No. 2}} \times 100$.

Reference: J. F. Kemp, ECON. GEOL., II., p. 6, 1907.

H. CLIFTON-MORENCI, ARIZONA.

	No. 1.	No. 2.	No. 3.	
SiO ₂	1.13	39.45	2.9	No. 1 = Average fresh Modoc limestone.
Al ₂ O ₃ } ..	1.76	33.42	5.3	No. 2 = Average garnet (andradite).
Fe ₂ O ₃ }				
MgO	1.62	?	?	
CaO	50.80	26.52	192.0	No. 3 = $\frac{\text{No. 1}}{\text{No. 2}} \times 100$.
CO ₂	41.66	—	∞	

The analysis of the fresh rock is only partial. The analysis of the altered phase is only of garnet. No account is taken of the other silicates.

Reference: U. S. G. S., Prof. Pap. 43, p. 71.

(Note.—In the diagram, where the analyses were sufficiently complete so that points were obtained on adjacent horizontal lines, these points are connected by full lines. When, however, no point was obtained on a certain line, the line joining the points on the lines above and below is broken.)

(b) The slope of the lines joining CaO, CO₂ and H₂O shows that there has been a relatively very great loss of CO₂, and a considerable relative loss of CaO. The slope of the lines joining CaO and CO₂ is evidence of the dissociation of part of the cal-

cium carbonate, and of the loss of CO_2 in the form of carbon dioxide. Since CaO is also lost relatively to SiO_2 , Al_2O_3 , and Fe , it is quite probable that much of the calcium carbonate was volatilized and driven off without dissociation.

The interpretation of these facts accords well with the hypothesis of the recrystallization of the original constituents of the limestone to form the "secondary silicates." It would be rather a difficult proposition to account for the approximate constancy of the silica-alumina-iron ratios by any theory of their introduction. If the ratios were nearly constant in only one case, and were quite different in the majority of cases, there would be but little difficulty about attributing the matter to mere coincidence. But in seven out of the eight examples, which seem to constitute at present all the available data, the ratios are found to be very nearly constant. It would be a remarkable coincidence, indeed, if the silica, alumina, and iron were each time added in almost exactly the same ratio as that in which they were present in the unaltered rock. In this connection it is instructive to note that the amounts of silica, alumina, iron oxides, etc., present in the fresh limestone depend *not* on silicate ratios, but upon the abundance of chert, kaolin, iron and magnesium carbonates, etc. By far the most reasonable explanation of this one feature is that the actual masses of these constituents varied but slightly during the alteration, but that the substances present in great excess were expelled, thus raising the percentages of those oxides in the rock.

If it be granted that there is about the same absolute amount of silica, alumina, and iron in the altered as there was in the fresh rock, a very great reduction in volume of the sediments must be accounted for. This state of affairs seems to be quite plausible for two reasons: in the first place there is, so far as known, scarcely anything in the density, texture, or structure of the contact phase to tell what proportion of the original volume of the limestone it represents. Two cases are cited in the tabulation above, in which reduction of volume is indicated by a dip of the limestone beds toward the Black Butte stock,¹ and by a crumpling

¹ W. H. Weed and J. Barrell, "Geology and Ore Deposits of the Elkhorn Mining District, Montana," U. S. G. S., 22d Ann. Rept., Part II., p. 444.

of interbedded gneisses in the Adirondack region.¹ In the second place, when a great batholith begins an upward journey, it makes way for itself in a manner not yet clearly understood—by marginal assimilation, by crowding the adjacent rock aside through faulting and folding, by overhead stoping, by eliminating easily soluble constituents in the wall rock, or by some combination of these processes. A reduction of volume of, say, 80 per cent. by contact metamorphism could be easily obscured by the advance of the batholith. To quote here from C. K. Leith,² in reference to the Iron Springs district: "As one stands on the edge of one of the large laccoliths in this district and is asked whether the 60-foot silicated phase represents an original 300 feet or original 80 or 90 feet, the difference linearly is so small as to have little effect on one's judgment."

There is a tremendous loss of carbon dioxide under any hypothesis. It does not seem probable that this loss should be made good by an introduction of new material, when the natural tendency is toward contraction of volume due to increased pressure, rather than that recrystallization and structural changes should obscure the evidences of contraction and incidentally afford space for the intrusive.

IV.

THE BEARING OF SOME PRINCIPLES OF PHYSICAL CHEMISTRY ON THE FORMATION OF THE "SECONDARY SILICATE ZONES."

With regard to the reactions that might take place between CaCO_3 , SiO_2 , kaolin, and H_2O under conditions of temperature and pressure such as exist at limestone contacts, very little is definitely known. Some experimental work, however, has been done that may have an important bearing on the problem. Several investigators have dealt with the subject of the dissociation of calcium carbonate. J. Königsberger³ published a table show-

¹ C. H. Smith, Jr., "Rocks of the Northwestern Adirondack Region," *Bull. Geol. Soc. Am.*, Vol. VI., p. 265, 1894.

² C. K. Leith, "Iron Ores of Iron Springs District, Utah—Reply to Review by J. F. Kemp," *ECON. GEOL.*, Vol. V., 1910, p. 188.

³ J. Königsberger, *N. J. Blgbd.*, XXXII., 1911, pp. 101-133.

ing the temperature-pressure relations for the dissociation of calcium carbonate to lime and carbon dioxide. He finds that for a temperature of $1,400^{\circ}$ C. a pressure of 80,000 atmospheres or 1,200,000 pounds per square inch is required to prevent the reaction. This pressure would involve a depth of about 20 miles. From this he argues that the presence of calcium carbonate as an inclusion or in contact with the magma is a safe maximum geological thermometer. Le Chatelier¹ also gives a table of the same temperature-pressure relations, but he deals with lower pressures. He finds that a temperature of 812° C. is sufficient to develop a pressure of one atmosphere. This is 78° lower than the figure given by Königsberger. Both of these experimenters worked under dry conditions. By taking average values for rock density and applying the results of these physicists, it is found that calcium carbonate existing at depths of 1,000 feet and 2,000 feet could only be dissociated at such temperatures as $1,150^{\circ}$ C. and $1,200^{\circ}$ C. respectively. Only rarely, if at all, are temperatures of this magnitude produced in the intruded rocks at such shallow depths.

It is evident, therefore, that some other factor must be very important. This is probably the presence of impurities such as silica, kaolin, and water. Gay-Lussac² makes the following statement: "Un courant d'air ou de vapeur d'eau facilite la décomposition du CaCO_3 , ce qui s'explique par l'élimination continue du gaz carbonique dégagé." Jacquelin³ finds that "à 100° C. en présence d'eau, la dissociation est déjà sensible." According to Bischof⁴ "when water is distilled over mixed carbonate of lime, magnesia, or spathose iron, with artificially prepared silica or powdered quartz, carbon dioxide passes over with the aqueous vapor." Such results as these indicate that the presence of kaolin and chert or quartz in limestone would greatly lower the temperature at which the lime-silicates would be formed. There are still at least two unknown factors in this reaction as it would take

¹ Le Chatelier, *Compt. Rend.*, Vol. 102, pp. 1,243, 1886.

² Gay-Lussac, *An. Ch. Ph.* (2), 63, 219, 1836.

³ Jacquelin, *Compt. Rend.*, 30, 106, 1850.

⁴ Bischof, "Chemical and Physical Geology," Vol. I., p. 7.

place in nature. In the first place, there is the effect of pressure on the temperature at which the reaction would occur. A calculation of molecular volumes in the reaction shows very little change, so it is probable that increase of pressure will not have a great effect. In the second place, there is the presence of such materials as Al_2O_3 , MgCO_3 , Fe_2O_3 , etc. No data are at hand by which their influence could be estimated. All that can be said is this—the presence of water and silica and probably other impurities seems to lower the temperature at which dissociation of calcium carbonate and the formation of lime-silicates may take place.

In order that complete dissociation of CaCO_3 under conditions of contact metamorphism may be accomplished, a means of escape must be provided for the carbon dioxide. This may be explained by the following quotation from J. V. Elsdén:¹ "At 812°C . the dissociation pressure of CaCO_3 is equal to one atmosphere. At this temperature, therefore, CaCO_3 can be completely dissociated in presence of CO_2 at atmospheric pressure. By increasing the pressure until the partial pressure of the CO_2 exceeds the dissociation pressure of CaCO_3 the latter does not dissociate, whatever may be the temperature to which it is exposed. It is important to note that this result depends upon the condition that the products of the reaction are not removed from the sphere of action. If the CO_2 is removed as fast as it is formed, dissociation can proceed at a far lower temperature since the dissociation equilibrium of the carbonate depends not upon the pressure to which it is subjected, but upon the partial pressure of the CO_2 in contact with it." Hence, as long as the CO_2 can be carried away so as to keep its partial pressure below the dissociation pressure of the carbonate, dissociation will continue to take place.

The above principle must have very important applications to the problem in hand, but it is almost impossible to approximate to these applications without a better knowledge of the actual conditions. In the different limestone contacts all degrees of

¹J. V. Elsdén, "Principles of Chemical Geology," p. 76.

partial dissociation are found. The amount of unaltered carbonate present varies from zero in some places to a considerable amount in others. This variation is no doubt partially due to the facility for escaping which the structural conditions after the intrusion gave to the carbon dioxide. There is a wide and interesting field of investigation in this very connection, but the data that are so far available are by no means adequate.

A clue might possibly be obtained as to whether or not fractures were present in the neighborhood of the magma at the time of its intrusion, by a study of rock structures and textures. If the age of the intrusion were definitely known a completely restored section of the intruded rocks might be made, although it would be on a rather ideal basis. This has been done in a few cases, and the depth of covering which lay over the cooling magma estimated. In each case, as the writer remembers, the intrusion took place distinctly into the zone of rock fracture. Means of escape for the dissociated CO_2 would then have been readily afforded.

Other suggestions might be afforded by a study of the textures of the igneous rock—whether phaneritic, porphyritic, or aphanitic. A coarse-grained rock evidently crystallizes very slowly, and therefore under a great depth of cover. Whether this depth is great enough to relegate the intrusion to the zone of flowage depends on the actual conditions in each case. A porphyritic rock, with a fine-grained matrix, must have been either intruded into cold rocks, or into hot rocks when it was very close to its point of crystallization. An aphanitic rock suggests very rapid cooling and a proximity to the surface.

There is another quite different aspect of the “secondary silicate zones” that is worthy of serious consideration. What is the connection between the chemical composition and texture of the igneous rock, and the character and extent of its metamorphic action? There are acidic rocks, ranging in texture from plutonic to felsitic, and there are basic rocks with all variations from plutonic to basaltic. A perusal of the literature reveals an apparent genetic connection of some sort. Basic rocks do not as a rule

produce as great a contact zone as acidic rocks. Ransome,¹ in his report on the Globe Copper District, Arizona, makes the following statement: "The metamorphic action of the diabase, even when intruded in great masses into quartzites and limestones, is remarkably slight. The only effect discoverable in the Globe limestone is the development of a little coarser crystalline texture which may extend for only a few inches from the contact." Lindgren² states in his report on the Clifton-Morenci District that "while the diorite-porphyrries have changed the surrounding sedimentary beds but little by the heat and emanations of the magma, the quartz-monzonite-porphyrries have generally exerted a profound alteration, especially in the Paleozoic limestones and shales." Kemp³ and other advocates of the direct introduction hypothesis use such facts as these to support their position. They relate the extent of the contact zone to the quantity of emanations proceeding from the magma. R. T. Chamberlin⁴ has shown that basic rocks contain more gases than acidic ones, and volcanics more than plutonics. From this it is argued that coarse-grained acidic rocks give off a greater quantity of gases on crystallization. Again, it is known that the minerals characteristic of acidic rocks are "low-temperature minerals,"⁵ that is, minerals that crystallize from fusion only with the aid of water, or other fluxes, solvents, or special reagents. Acidic magmas, then, before crystallization are well provided with mineralizers. These must be freely given off on crystallization. A very striking case, however, of an extensive contact zone around basic intrusives is seen in the Lake Superior district, where the Duluth gabbro intrudes the iron formation sediments, converting them into amphibole-magnetites, jaspilites, and hard ores.

From the point of view of the recrystallization hypothesis, it is admitted that these mineralizing gases play an important part in the formation of the second phase of the metamorphic zone,

¹ F. L. Ransome, U. S. G. S., Prof. Pap. 12 (pp. 85-86).

² W. Lindgren, U. S. G. S., Prof. Pap. 43 (pp. 85, 126).

³ J. F. Kemp, "Types of Ore Deposits."

⁴ R. T. Chamberlin, "Gases in Rocks," Publication 106, Carnegie Institution of Washington, 1908.

⁵ A. Harker, "The National History of Igneous Rocks," p. 284.

but it is maintained that this period of emission is decidedly later than that of the formation of the first phase. It remains, then, to correlate the extent of this phase, not to the quantity of mineralizers given off by the intrusive, but to the temperature and pressures at which the different magmas crystallize, and to the nature of the intruded sediments. Sufficient data have been cited to show that the formation of the silicates is genetically related to the presence of impurities in the limestone; but at present it would be difficult to establish such a connection between the zones and the temperatures of crystallization of the intrusives.

V.

A STUDY OF THE HEAT CONDITIONS ACCOMPANYING AN INTRUSION.

A new feature enters the problem when the time element is considered in connection with the transfer of heat. It has been commonly conceded that the formation of the contact zones is not the affair of a moment, but it is scarcely wrong to say that no adequate estimate of the length of time during which a difference of temperature between intruded and intrusive rocks is sustained has yet been made. No such estimate, at least, appears in the literature.

Some very interesting results based on calculations of this nature have been kindly given to the writer by Dr. L. R. Ingersoll, of the physics department of the University of Wisconsin. Owing to the impossibility of getting data, at present, as to the specific heat, density, and thermal conductivity at the temperatures of intrusive magmas, the results can necessarily be only approximations. Allowing for transfer of heat by conduction alone, and making probable corrections in the different factors for the high temperature of magmas, a result such as that given below would be obtained. Considering that the temperature of the granite at the beginning was 1000°C. , and that of the limestone 100°C. , the application of the following formula will

give a temperature of the bounding plane between 690° C. and 755° C.

$$\theta = \left\{ \frac{K_1 \theta_1}{h_1} + \frac{K_2 \theta_2}{h_2} \right\} / \left\{ \frac{K_1}{h_1} + \frac{K_2}{h_2} \right\}$$

where θ = temperature of bounding plane in $^{\circ}$ C.,

K_1 = conductivity of granite at ordinary temperatures
= 0.0081,

h_1 = diffusivity of granite at ordinary temperatures
= $\sqrt{0.0155}$,

θ_1 = temperature of magma in $^{\circ}$ C.,

θ_2 = temperature of limestone in $^{\circ}$ C.,

K_2 = conductivity of limestone at ordinary temperatures
= 0.0050,

h_2 = diffusivity of limestone at ordinary temperatures
= $\sqrt{0.0092}$.

In order to get limiting values for θ , the following alterations were made in the values of K_1 and h_1 :

- (1) $\left\{ \begin{array}{l} K_1 \text{ was multiplied by 3, and} \\ h_1^2 \text{ was multiplied by 2.} \end{array} \right.$
- (2) $\left\{ \begin{array}{l} K_1 \text{ was multiplied by 1.5 and} \\ h_1^2 \text{ was multiplied by 1.} \end{array} \right.$

It seems quite certain, therefore, that the temperature of the boundary plane should lie somewhere between the two results obtained. A very important modification of the result will be obtained when allowance is made for the transfer of heat by convection currents, from the interior to the periphery of the igneous mass. By this means, the temperature at the contact will be maintained somewhat near that in the interior. The temperature of the boundary plane given above will therefore be too low, and it is not improbable that something like 900° or 950° may be reached.

The rate at which heat is transferred from the hot to the cool rock is far more important than the actual temperature at the

contact. The following diagram has been constructed by Dr. L. R. Ingersoll to represent the rate of advance of the heat wave through average rocks. The factors used in the calculation were

FIG. 13. Diagram showing progress of heat waves from a cooling laccolith 1,000 meters in radius, with initial temperature of 1000° C.

average ones, and little allowance was made for the different character of the two rocks. Nevertheless, the results are very interesting and important. They show that under those conditions a difference of temperature of about 50°C . still obtains between points two hundred meters on either side of the contact, ten thousand years after the intrusion.

No doubt, corrections to be made for the different characters of the rocks, and allowance for convection in the magma would substantially change the position of the curves, but it is unlikely that the amount of time required to produce equality of temperature in both rocks would be materially altered. This factor of time is the important one geologically.

INTERPRETATION AND RESULTS.

From Fig. 13 it is evident that the limestone for considerable distances from the contact receives a marked accession of heat from the intrusive. With the gradual advance of the magma, the outer edge of the heated zone maintains a position at a considerable distance within the limestone. Due to this rise of temperature, and to pressure exerted by the intruding magma, the limestone must necessarily be under a great degree of compression. Provided the pressure is not too great, the high temperature will cause the dissociation of the calcium carbonate, and the formation of lime silicates. The pressure will constantly tend to diminish the volume, and to eliminate pore space during the process of recrystallization.

Each zone in the limestone, parallel to the contact, will experience a continuous rise of temperature, until a maximum is reached. Subsequent to this, a cooling will set in, accompanied by a contraction of the hot limestone. As this cooling and consequent contraction proceed, tension fractures will develop, and these may give rise in the later stages to persistent fissuring. During this stage of the contact action, the emission of mineralizing solutions from the magma will be most abundant, and in the natural course of events they should deposit their load in the fissures and small openings thus afforded, and replace the pre-

viously metamorphosed limestone in the walls. For each particular zone in the limestone these two stages of recrystallization, and infiltration of pneumatolytic constituents, are sharply differentiated in time; but it must be noted that while the limestone at a considerable distance from the intrusive is in a state of rising temperature and compression, that near the intrusive may have already passed the maximum and be in a condition where fissures are developing.

The recent paper by Spurr, Garrey, and Fenner¹ on the Matehuala District, Mexico, affords data which go far towards validating this course of reasoning. These geologists actually find that the first structural effect of the intrusion on the limestone was a shattering and recrystallization due to increased pressure, and that it was followed later by the gradual development of persistent fissures, which are filled by a series of the younger minerals.

There is another fact that is rendered exceedingly important by the discovery that the length of time during which there is a difference of temperature between the limestone and the igneous rocks is not a matter of a few years, but rather of thousands of years. This new factor is the activity of the underground circulating waters. While the intrusive is still hot, there is abundant opportunity for the waters to work it over and leach from it metallic and other constituents, which might later be deposited in other parts of the intrusive or in the "secondary silicate zone" of the limestone. This interpretation is practically the same as Lawson's hypothesis of the disturbance of the underground water, with the exception, of course, that Lawson does not allow of the formation of the "secondary silicates" by heat and pressure alone, but attributes the formation of the whole zone to the one cause.

If the above suggestion as to the work of heated underground (both meteoric and magmatic) waters be correct, a considerable burden of work formerly attributed to magmatic emanations is shifted to another agency.

¹Spurr, Garrey, and Fenner, "Study of a Contact Metamorphic Ore-Deposit. The Dolores Mine, at Matehuala, S. L. P., Mexico," *ECON. GEOL.*, Vol. VII., p. 444.

The balance of evidence consequently seems to be quite in favor of the origin of the "secondary silicate zones" by the elimination of excess CaCO_3 , and the recrystallization of the impurities into lime silicates. Of course, there are many features of contact zones described from the different camps that do not seem to be in harmony with the hypothesis, but such discrepancies may be largely due to the personal equation which inevitably influences observations and inferences.

Acknowledgments are especially due to Dr. C. K. Leith, and Mr. W. J. Mead, of the University of Wisconsin, for the interest they manifested, and the assistance they gave during the preparation of this paper.

Appended is a complete bibliography of the references used in the preparation of the paper, which have not previously been given.

BIBLIOGRAPHY.

- SPENCER, SALISBURY, KÜMMEL, PALACHE AND WOLFF. U. S. G. S., Folio 161 (Franklin Furnace, N. J.).
- H. C. BEELER. Mining in the Grand Encampment Copper District, Wyoming. Cheyenne, Sept. 1, 1905.
- C. R. VAN HISE. Metamorphism of Rocks and Rock Flowage. *Bull. Geol. Soc. Am.*, Vol. IX., p. 311.
- CHAS. PALACHE. Simultaneous Crystallization of Epidote, Specularite, Garnet. *Am. Jour. Sc.*, 3d series, VIII., 1899, p. 299.
- J. G. AGUILERA. The Geographical and Geological Distribution of the Mineral Deposits of Mexico. *Trans. A. I. M. E.*, XXXII., 1902, p. 503.
- W. LINDGREN. Metasomatic Processes in Fissure Veins. *Trans. A. I. M. E.*, XXX., p. 611.
- J. E. SPURR. Ore Deposits at Aspen, Colorado. *ECON. GEOL.*, IV., 1909, p. 301.
- SPURR AND GARREY. Economic Geology of the Georgetown Quadrangle. U. S. G. S., Prof. Paper 63.
- G. W. HAYES. The Albany Granite, N. H., and its Contact Phenomena. *Am. Jour. Sc.*, Jan., 1881, p. 21.
- E. P. JENNINGS. The Origin of the Magnetic Iron Ores of Iron County, Utah. *Trans. A. I. M. E.*, XXXV., 1903, p. 338.
- R. T. HILL. The Occurrence of Hematite and Martite Iron Ores in Mexico. *Am. Jour. Sc.*, Vol. XLV., 1893, p. 112.

- J. S. DILLER. The Iron Ores of the Redding Quadrangle, Calif. U. S. G. S., Bull. 213, pp. 219-220.
- C. R. KEYES. The Iron Deposits of the Chupadera Mesa. *Eng. and Min. Jour.*, LXXVIII., 1904, p. 632.
- F. L. NASON. A Report on the Iron Ores of Missouri. *Miss. Geol. Surv.*, II., 1892, pp. 1-365.
- A. C. SPENCER. Genesis of the Magnetite Deposits in Sussex County, N. J. *Min. Mag.*, X., 1904, pp. 377-381.
- R. W. BROCK. Preliminary Report on the Rossland District, B. C. *Geol. Surv., Can.*, No. 939.
- E. LINDEMAN. Magnetite Deposits of Texada and Vancouver Ids. *Jour. Can. Min. Inst.*, XIII., 1910, p. 107.
- E. T. COX. Discovery of Oxide of Antimony in Extensive Lodes in Sonora, Mexico. *Am. Jour. Sc.*, 3d series, XX., 1880, p. 421.
- EDWARD HALSE. Notes on the Antimony Deposit of El Altar, Sonora, Mexico. *Trans. Fed. Inst. Min. Eng.*, VI., 1893-4, p. 290.
- S. F. EMMONS. The Little Cottonwood Granite of the Wasatch Mts. *Am. Jour. Sc.*, 4th series, XVI., Aug., 1903, p. 145.
- J. F. KEMP. Geology of the Magnetites near Port Henry, N. Y., and Especially Those at Mineville. *Trans. A. I. M. E.*, XXVII., p. 146.
- A. KEITH. Iron Ore Deposits of the Cranberry District, North Carolina-Tennessee. U. S. G. S., Bull. 213, 1902, pp. 243-246.
- L. G. WESTGATE. The Mineralogical Characters of Certain New Jersey Limestones. *Am. Geol.*, XIV., 1894, p. 308.
- J. P. IDDINGS. The Eruptive Rocks of Electric Peak and Sepulchre Mountain, Yellowstone National Park. U. S. G. S., 12th Ann. Rept., Part I., p. 569.
- F. W. CLARKE. Mineral Analyses from the Laboratories of the U. S. G. S., 1880 to 1903. U. S. G. S., Bull. 220, 1903.
- E. C. HARDER. Magnetite Deposits near Dillsburg, Pa. *ECON. GEOL.*, V., p. 599.
- C. K. LEITH. Iron Ores of the Western United States and British Columbia. U. S. G. S., Bull. 285, p. 194.
- A. HARKER AND J. E. MARR. The Metamorphic Rocks Around the Shap Granite. *Quart. Jour. Geol. Soc.*, XLIX., Part III., Aug., 1893, pp. 368, 369.