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

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INTRODUCTION.

During the last ten years, the number of ore deposits which have been found at the contacts of intrusive igneous rocks with limestones has rapidly increased. This has been in part the result of the clearer understanding and the easier recognition of this type of deposits which the study of contact metamorphism and ore deposition has brought about. The investigation of the increasing number of deposits has naturally led to a discussion as to the exact manner in which such bodies of ore have originated. A number of different hypotheses have been advocated for the formation both of the ores and the contact metamorphic minerals which have been developed by the intrusive igneous rocks in limestones. There has been not a little controversy between those who advocate the different methods of genesis. As all geologists and mining engineers may not be entirely familiar with the arguments which have been presented by those who favor one or the other of the proposed hypotheses, and because more attention has been given to the origin of the associated ores than to the study of the very extensive portions of the contact zones where little or no ore has been found, the writer feels that the following critical review of the existing theories is warranted.

Inasmuch as the ores which are associated with these contact zones occupy but a small portion of the contact area, more attention will be given to the non-metalliferous portion than to that which is composed chiefly of ore bodies. The sources of information are the various published reports which have been written on those districts which are of economic importance, as they constitute the major portion of the available literature on the subject. Those facts which seem to have general significance have been tabulated in the following pages, and it is hoped that the reader may obtain from these tables a clearer idea as to the relative amount of accurate observation which supports either one or the other of the two most important hypotheses. It is the writer's intention to follow this review of the literature by a paper based upon extensive field observation.

GENERAL CHARACTERISTICS OF LIMESTONE CONTACTS.

Distribution.—Contacts of limestones with intrusive igneous rocks occur in greatest number in the western part of the continent of North America. They are here developed along the borders of extensive batholiths of igneous rock which have invaded sedimentary series and which have been revealed at the surface by the erosion of the overlying covers. In the eastern part of the continent they are less abundant. Some important ones occur, however, in the Adirondacks, the highlands of New Jersey, and the Piedmont district. The metamorphosed sedimentary rocks here are mostly Algonkian or Paleozoic. The sediments in these eastern occurrences have probably been subjected to repeated dynamic metamorphism, so that all, or nearly all, evidence of early contact action has been completely obliterated. In the western occurrences, on the other hand, the invaded rocks are frequently of late Paleozoic or early Metazoic age, and the contact zones, except for weathering, remain today in practically their original condition. They furnish, therefore, excellent opportunities for critical study.

Invaded Rocks.—The sedimentary rocks into which the intrusives have made their way are not exclusively limestones. Shales, sandstones, and conglomerates are of frequent occurrence. There are, of course, gradations between all of these different types. Limestones frequently contain sand or clay; sandstones, lime, clay, or iron; while the shales may contain lime or sand. In nearly all of the western occurrences a variety of sedimentary rocks are present, and all of the main types of sediments with the intermediate gradations are more or less extensively represented. Upon all of these sediments the intrusives have exerted contact effect, but the ore bodies which are occasionally found along the igneous contacts are most commonly developed in the limestone.

Associated Ores.—Many of the ore deposits which are developed along these limestone contacts are sufficiently extensive and of sufficient value to be of considerable commercial importance. This is particularly true in the case of iron and copper. Iron is found in such association as magnetite[1] and specularite;[1] copper occurs very frequently as chalcopyrite and bronite, tetrahedrite and cupriferous pyrites;[2] lead and zinc are occasionally found as galena and sphalerite;[3] native gold occurs in wollastonite at Chiapas, Mexico,[4] and in arsenopyrite on the Simillkameen River, B. C.;[5] platinum is found in wollastonite;[6] bismuth occurs as tetradymite and bismuthinite;[7] and silver[8] as argentite, associated usually with the copper deposits. Of the above-named metal-bearing minerals, iron and copper alone occur in bodies of sufficient size and value to be of commercial importance. In number and extent the iron deposits overshadow the copper, and it is only necessary to mention, in the case of copper, the camps at Clifton-Morenci, etc. Gold, silver, lead, and zinc are occasionally recovered as by-products.

[1] C. K. Leith and E. C. Harder, "The Iron Ores of the Iron Springs District, Utah," U. S. G. S., Bull. 338, 1908.

[2] E. C. Harder, "Iron Ores of Western and Central California," U. S. G. S., Bull. 430; F. L. Ransome, U. S. G. S., Prof. Paper 21 (Bisbee); W. Lindgren, U. S. G. S., Prof. Paper 43 (Clifton-Morenci).

[3] W. O. Crosby, "The Limestone-Granite Contact-Deposits of Washington Camp, Arizona," *Trans. A. I. M. E.*, XXXVI., 1905, p. 626.

[4] E. T. McCarty, "Mining in the Wollastonite Ore-Deposits of the Santa Fe Mine, Chiapas, Mexico," *Trans. Inst. Min. and Met.*, Vol. IV., 1896, pp. 169–189.

[5] W. H. Weed, "Ore Deposits near Igneous Contacts," *Trans. A. I. M. E.*, XXXIII., 1903, p. 734.

[6] L. Hundeshagen, "The Occurrence of Platinum in Wollastonite on the Island of Sumatra," *Trans. Inst. Min. and Met.*, July 21, 1904.

[7] W. H. Weed, "Ore Deposits near Igneous Contacts," *Trans. A. I. M. E.*, XXXIII., 1903, p. 733.

[8] W. Lindgren, "Copper Deposits of the Seven Devils, Idaho," U. S. G. S., 20th Ann. Rept., Part III., p. 249; E. T. McCarty, *op. cit.*

Contact Metamorphic Minerals.—Associated with the metallic minerals are gangues of lime silicates and other contact metamorphic minerals, which show no marked variation whether iron or copper minerals preponderate in the ore.

Below is a list of the common "contact-metamorphic" minerals. They have been arranged in two distinct groups. Group 2 includes those minerals which contain elements such as boron, fluorine, chlorine or for other reasons later discussed may be admittedly the products of igneous emanation; group 1 contains the disputed series of what will be here termed the "silicate zone" group. It is mainly about this group that discussion has arisen.

GROUP 1.	GROUP 2.
Grossularite (Ca, Al, SiO_2).	Scapolite (Ca, NaCl, Al, SiO_2).
Andradite (Ca, Fe, SiO_2).	Vesuvianite (Ca, Al, F, SiO_2, OH).
Epidote (Ca, Al, Fe, SiO_2, H_2O).	Quartz (SiO_2).
Diopside (Ca, Mg, SiO_2).	Muscovite (H, K, Al, SiO_2).
Tremolite (Ca, Mg, SiO_2).	Albite (Na, Al, SiO_2).
Actinolite (Ca, Mg, Fe, SiO_2).	Axinite (Ca, Al, Fe, Mn, B, SiO_2).
Wollastonite (Ca, SiO_2).	Apatite (Ca, F, Cl, P_2O_5).
Biotite (Mg, Fe, Al, SiO_2, H_2O).	Tourmaline (Fe, Mg, B, Al, SiO_2).
Calcite ($CaCO_3$).	Fluorite (CaF_2).
Quartz (SiO_2).	

RELATIVE SUCCESSION OF THE TWO GROUPS.

Although the ore minerals are generally intergrown with the secondary silicates there is much which indicates a difference in the time of formation of the metalliferous and gangue minerals. Metallographic methods have been used on specimens, and in many cases a definite order of crystallization has been determined. Kemp has shown that at San Jose, Mexico,[1] and at White Knob, Idaho,[2] the ore-minerals were formed later than the silicates, and often cut through them as veinlets. Leith and

[1] J. F. Kemp, "The Copper Deposits of San Jose, Tamaulipas, Mexico," *Trans. A. I. M. E.*, XXXVI., 1906, pp. 178–203.

[2] J. F. Kemp and C. G. Gunther, "The White Knob Copper Deposits, Mackay, Idaho," *Trans. A. I. M. E.*, XXXVIII., 1907, pp. 269–293.

Harder, in their Iron Springs bulletin,[1] establish a succession of first, silicate minerals and second, ore-minerals. Barrell[2] draws attention to the same feature at Marysville, Montana. Stutzer[3] determined the following order at the White Horse Pass mines in the Yukon: (*a*) pyroxene, and rarely magnetite, (*b*) magnetite, (*c*) garnet with a few metallic sulphides, (*d*) amphibole and the greater part of the sulphides, (*e*) calcite. At Morenci, Arizona, Lindgren[4] records the simultaneous crystallization of the lime-silicates and magnetite, together with some of the sulphides, while a great part of the sulphides are plainly of later formation, and cut the earlier minerals in veinlets and stringers. Spurr and Garrey[5] reach a similar conclusion in their observations upon the garnet-zones of Velardeña, Mexico; and Ransome,[6] in his new professional paper on the Breckenridge District, Colorado, concedes a dual stage.

HYPOTHESES OF ORIGIN.

The chief point on which geologists differ is as to the mode of origin of both the silicate and ore-minerals. The main views may be given in brief:

1. All the minerals of the contact-zone are the result of recrystallization of substances present before the limestone was metamorphosed. Ore-minerals and silicate-minerals are of the same origin. No introduction of material from the intrusive has occurred. This is the hypothesis which Rosenbusch,[7] Zirkel[8]

[1] C. K. Leith and E. C. Harder, "The Iron Ores of the Iron Springs District, Utah," U. S. G. S., Bull. 338, 1908.

[2] J. Barrell, "Geology of the Marysville Mining District, Montana," U. S. G. S., Prof. Paper 57.

[3] O. Stutzer, "Die Kontaktmetamorphen Kupfererzlagerstaeten von White Horse, Yukon," *Zeitschr. für prakt. Geol.*, March, 1909, p. 120.

[4] W. Lindgren, "The Copper Deposits of the Clifton-Morenci District," U. S. G. S., Prof. Paper 43, 1905.

[5] J. E. Spurr and G. H. Garrey, "The Copper Deposits of the Velardeña District, Durango, Mexico," ECON. GEOL., Vol. III., p. 688.

[6] F. L. Ransome, "Geology and Ore Deposits of the Breckenridge District, Colorado," U. S. G. S., Prof. Paper 75, 1911.

[7] Rosenbusch, "Mikroskopische Physiographie," 3d ed., p. 85.

[8] Zirkel, "Lehrbuch der Petrographie," 2d ed., Vol. I., pp. 587–588.

and Brögger advocate and may be entitled the old or original hypothesis.

2. A commonly accepted view at the present time is that of which J. F. Kemp[1] seems to be the chief supporter. It is almost diametrically opposed to that of Rosenbusch, Zirkel and Brögger. According to Kemp, the limestone furnishes only lime and some carbon dioxide to the minerals of the contact-zone. He maintains that the intrusive on cooling emits great quantities of vapors containing SiO_2, Al_2O_3, Fe_2O_3 FeO, MgO, H_2O, as well as metallic sulphides and oxides. The silica, alumina, and iron oxides unite with the lime of the limestone to form lime silicates. Of course, if the original limestone should contain silica, alumina, or iron oxide as impurities, they might well be used in the formation of the secondary minerals.

3. There are other views which seem more reasonable in that they take a sort of intermediate position with regard to the above-mentioned two:

(*A*) J. Barrell:[2] A period of metamorphism follows the intrusion, during which gases are expelled from the sediments, the volume contracts, and there is a general recrystallization. Subsequent to this comes a period of metasomatism, during which a replacement of the metamorphosed sediments takes place, the replacing material coming as eruptive afteractions from the intrusive. According to this view, the silica and alumina existing in carbonate rocks combine with the bases and set free a proportionate amount of carbon dioxide. The absolute amount of lime and magnesia is the same after the process is completed as before. The emanations, which proceed from the magma, during the metasomatic phase of the contact action, consist chiefly of silica, iron oxide, water, sulphur, besides, of course, other ore-producing compounds.

[1] J. K. Kemp, "Contact Deposits: Types of Ore Deposits," *Mining and Scientific Press,* 1911.

[2] J. Barrell, "Geology of the Marysville Mining District, Montana," U. S. G. S., Prof. Paper 57; "Physical Effects of Contact Metamorphism," *Am. Jour. Sc.,* 1902, pp. 279–296.

(*B*) A. C. Lawson:[1] The heated intrusive disturbs the groundwater circulation, and gives it new impetus to work over the rocks of the vicinity. This increased activity of the ground-water is responsible, then, for the formation of both the secondary silicates and the ores. In this way, Lawson avoids the necessity of looking for a contribution from the magma. In his own words: "The circulation would always be upward on the periphery of the hot mass. . . . Such a circulation of the heated ground-water would be quite competent to do all that is ascribed to magmatic waters, including the formation of lime-silicate zones."

(*C*) W. Lindgren:[2] There is a combination of a recrystallization of impurities with an introduction of large amounts of SiO_2 and Fe_2O_3, and small amounts of Al_2O_3, to form the secondary silicates. The ore-minerals are partly formed at the same time as the silicates, and are partly the result of a working over of the intrusives by hot waters. In his earlier work,[3] he states that the "metallic-minerals are intergrown with the various gangue minerals,—garnet, epidote, wollastonite, etc.—in such a manner that they must be considered as having a simultaneous origin. The theory of a subsequent introduction of the metallic ores is decidedly untenable." More recently, however, he has come to recognize more or less definitely a sort of dual stage in the formation of the contact-zones.

(*D*) C. K. Leith:[4] According to the hypothesis set forth by Leith and Harder in their Iron Springs bulletin, the secondary silicate zone is largely a recrystallization of constituents already in the limestone, combined with an expulsion of the excess calcium carbonate. This view does not by any means involve a total absence of infiltrated material from the intrusive, but its advocates maintain that the so-called contact-zone can be litholog-

[1] A. C. Lawson, "Types of Ore Deposits—A Review," *Min. and Sc. Press*, Feb. 3, 1912, p. 200.

[2] W. Lindgren, "Copper Deposits of the Clifton-Morenci District, Arizona," U. S. G. S., Prof. Paper 43, 1905.

[3] W. Lindgren, "The Character and Genesis of Certain Contact-Deposits: Genesis of Ore-Deposits," 1901, p. 726.

[4] C. K. Leith and E. C. Harder, "The Iron Ores of the Iron Springs District, Utah," U. S. G. S., Bull. 338, 1908.

ically divided into two parts, one part of which is formed entirely by recrystallization in the early stages of the metamorphism, and the other part by later addition of material in the way of emanations from the magma. The minerals which belong to the first class are those mentioned in the left-hand columns on pages 7 and 8, while those of the second class include among others those listed in the right-hand column on the same pages, together with the metallic minerals. It will be noticed that the non-metallic minerals of the latter class nearly all contain an element more or less foreign to sedimentary series, *e. g.*, boron, fluorine, chlorine, beryllium, etc. These are typically found in magmatic emanations. The metallic minerals may be either direct contributions from the magma, or hot water deposits resulting from the working over of the hot intrusives. Definite evidence is obtained in the area described of the earlier formation of the first class of minerals. The two periods no doubt overlapped, but there is a somewhat well-marked distinction in the matter of time.

The magnitude of the iron deposits of the West, especially as they occur in connection with acidic intrusives, makes it almost impossible to suppose that they have been formed in any other way than by direct introduction from the cooling magma.[1] The copper deposits, on the other hand, are low grade and are disseminated. The igneous rocks with which they are associated show the results of leaching by hydrothermal action, and also contain traces of copper. There seems to be no reason why the copper could not have been at least partially contributed by the hot waters that leached the intrusives.[2]

The last hypothesis seems to the writer to be the most probable. In the present paper, an attempt is made to collect and correlate facts that will tend to substantiate this hypothesis. During the discussion, the application of the expressions "secondary silicate zone," "contact-zone," etc., will be limited to that phase characterized by the presence of the minerals of the first class, as

[1] Personal communication.

[2] Personal communication.

mentioned above. It is freely admitted that minerals containing such elements as boron, fluorine, beryllium, etc., required for their formation a contribution from igneous sources.

TABLE OF COMPARATIVE EVIDENCE.

Setting aside the question of how and when the ore-minerals of the contact-zones were formed, the problem resolves itself into the following alternative: (*a*) Is the "secondary silicate zone" the result of a combination of the lime of the limestone with other oxides furnished directly by the intrusive, or (*b*) is it entirely the result of a redistribution and recrystallization of the impurities already in the limestone, without any contribution from the magma?

The evidence obtainable from published articles which deal with this question has been arranged in two columns in the following tabulated summary. Arguments from each individual publication are presented together, on one side or other of the center line according to the view to which they lend support. Facts which equally favor or oppose both hypotheses are not noted in the compilation. Letters and figures appended to the various paragraphs thus: (*A,* pp. 199–200) refer to the list of references on page 45 of this paper.

COMPARATIVE TABLE OF EVIDENCE SUPPORTING THE TWO OPPOSING HYPOTHESES OF ORIGIN OF SECONDARY SILICATE ZONES.

CRITERIA FAVORING THE HYPOTHESIS OF THE RECRYSTALLIZATION OF IMPURITIES TO FORM THE SILICATES, AND THE LATER INTRODUCTION OF METALLIC AND PNEUMATOLYTIC CONSTITUENTS.	CRITERIA FAVORING THE HYPOTHESIS OF THE DIRECT CONTRIBUTION FROM THE MAGMA OF BOTH METALLIC CONSTITUENTS, AND MATERIALS FOR THE FORMATION OF THE SILICATES.
1. The view that now appears to be generally accepted, *i. e.*, the introduction of ore minerals later than the formation of the silicates, favors to a certain extent the recrystallization hypothesis (*A*, pp. 199–200).	1. The largest contact zones seem to be found in association with acidic intrusives. Magmas of acidic composition are believed to be most richly provided with the so-called mineralizers (*A*, p. 191).
2. Garnet rock (grossularite) occurs along part only of the contact and coincides with the impure limestone layers (*B*, p. 630).	
3. Wollastonite commonly occurs as a "reaction-zone bordering layers and nodules of chert in those portions of the cherty limestone nearest the granite or within several hundred feet of the contact. The relations are very clear, the chert masses, often with frayed and disintegrated margins, being separated from the enclosing crystalline limestone by zones from one to several inches broad of white massive wollastonite. . . . That the silica of the chert had	

replaced the carbon dioxide of the limestone is obvious" (*B*, p. 634).

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4. In the Washington Camp, Arizona, the garnet-zones are very persistent. They disregard the granite contact, and follow each a particular bed or horizon of impure limestone longitudinally through the district. "Of especial interest and significance among these is the garnet-zone at the base of the limestone, in the siliceous and argillaceous beds of passage between the basal quartzite and the limestone, and separated by the quartzite, from 100 to 200 feet thick, from the western granite" (*B*, p. 636).

5. "If the SiO_2 and Al_2O_3 have been derived from the granite, and the limestone has furnished only the CaO, MgO, Fe_2O_3, the garnet-zone should be a constant feature of the contact; or, at least, there is no apparent reason why it should fail, as it does, just where SiO_2 and Al_2O_3 are wanting in the limestone" (*B*, pp. 637–638).

6. In the White Knob Camp, Mackay, Idaho, the secondary silicate zone at the contact of the quartz porphyry and limestone is small. However, where

DIRECT CONTRIBUTION.

2. Kemp shows by analysis that the garnet-rock at White Knob is largely andradite, the calcium-iron garnet. He argues that the amount of iron

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
the intrusive completely engulfed fragments of limestone, an almost complete alteration to garnet had taken place. The explanation seems to be one of the amount of heat transferred to the limestone, and the temperature to which it was raised. Of course, the included fragments would be heated to a much higher temperature than the country rock in place (*C*, p. 285).	required for this mineral cannot be obtained from the limestone (*C*, pp. 286–7).
7. Diopside is the next abundant silicate after garnet, at White Knob. This is free from iron, and should be averaged up with the andradite in order to get a correct idea of the composition of the silicate zone. This would greatly reduce the percentage of iron required in comparison with the silica and alumina (*C*, pp. 287–288).	
8. Kemp recognizes two periods in the formation of the contact zone; garnet, diopside, vesuvianite and epidote seem to have been formed first, while magnetite, chalcopyrite, pyrite and specularite were formed a little later (*C*, p. 289). This is a common feature in many of the camps, and it seems difficult to reconcile the phenomenon in so many cases with the hypothesis of direct contribution.	

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
9. The amount of aluminous silicates present in the secondary zone at White Knob seems a strong argument against the introduction of materials, for the reason that Al_2O_3 is practically unknown in emanations from igneous rocks.	
10. The invaded limestone at White Knob contains considerable percentages of impurities in the way of carbonaceous material, bands of chert, and beds of dolomitic limestone. There seems to be but little occasion for trying to account for these materials by direct contribution (*C*, p. 276).	
11. The invaded sediments at the Bisbee Camp, in which the contact zone occurs, are, according to Ransome's own description anything but pure calcium carbonate. There are beds of chert, dolomite and shale interlayered with limestone. Even in the so-called pure beds of Escabrosa and Naco limestone, in which the copper ores occur, are found beds of chert, and others of pink calcareous shale. Examined with a lens these limestones show minute quartz grains, and tiny flakes of mica. Ransome gives analyses of the Naco limestone, for instance, but admits (p. 55) that on the average it contains	3. The original metallic mineral at Bisbee is pyrite. It occurs very intimately associated with the secondary silicates, and appears to have been crystallized at the same time as the silicates (*D*, p. 132).

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
noticeable amounts of silica, alumina, and iron oxides (*D*, pp. 28–56). 12. A thin section of the Naco limestone at Bisbee, near the contact, shows that, although it is apparently unchanged to the naked eye, it is "nearly one-third altered into a granular aggregate of quartz forming an irregular web inclosing residual kernels of calcite" (*D*, p. 83). (Why should the quartz enclose kernels of crystalline limestone, unless it was the result of recrystallization of chert already in the limestone?) 13. The sediments in the Clifton-Morenci Camp, in which the contact zone occurs, seem from Lindgren's descriptions to contain a considerable amount of silica, alumina, magnesia, and iron oxide, in the form of chert, shale, dolomitic bands, and brownish limestone. It seems hardly necessary to require the introduction of just these materials to form the silicates (*E*, pp. 62–73). 14. Lindgren finds the quartz grains in the intrusive rocks in the Clifton-Morenci Camp to contain abundant fluid inclusions. These inclusions contain usually a solid body resembling specularite.	4. "While the diorite-porphyries have changed the surrounding sedimentary beds but little by the heat and emanations of the magma, the quartz-monzonite-porphyries and the granite-porphyries have generally exerted a profound alteration, especially in the Paleozoic limestones and shales" (*E*, p. 85). 5. "When the dike enters the pure limestone of the Modoc formation, garnet forms in enormous quantities. A stratum of garnet and magnetite follows this bed for 2,000 feet between almost *unal-*

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He regards it as a very curious fact that only very exceptionally do the secondary minerals of the contact zone contain such inclusions. "The metamorphism of the limestone to garnet, epidote, diopside, quartz, and other minerals took place under conditions of high temperature and pressure, and almost certainly in the presence of aqueous solutions in fluid or gaseous form." (These facts indicate that the quartz of the intrusive and the quartz of the contact zone have had quite different origins.) (*E*, pp. 214, 217.)

15. "The change in composition in the case of clay shales is extremely slight" (*E*, p. 162) (*E*, p. 130). (If the metamorphism is caused by addition of substances, how is it that shales become recrystallized and form silicates, and yet show only very slight changes in chemical composition?)

16. In the Clifton-Morenci district: Sandstones are altered to quartzites. Shales are altered to epidote-amphibole, schists and pyrite. Limestones are altered to iron-garnet, and diopside rocks (*E*, p. 127). (These are the natural recrystallizations of the respective sediments.)

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tered Devonian and Cretaceous sediments (*E*, p. 127).

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17. Lindgren gives figures in the Clifton-Morenci professional paper to show the tremendous transfusion of material that would be necessary on the direct contribution hypothesis for the change of limestone to garnet, provided there were no change of volume. To accomplish this result, 460 kilograms CaO and 1.19 kilograms CO_2 would have to be expelled per cubic meter, while 1,330 kilograms SiO_2 and 1,180 kilograms Fe_2O_3 would have to be added (*E*, p. 154). (This is demanding as much from the intrusive as the recrystallization theory demands from the limestone.)

DIRECT CONTRIBUTION.

6. Garnet formations (the largest of which is 200 feet thick) are often entirely enclosed by granite, and appear to have no relation to limestone (*F*, p. 472). (Limestones, however, are present in the immediate neighborhood.)

7. The general presence of copper sulphides in these garnet-reefs, together with an excess of silica, shown by the presence of quartz, gives the garnet-reefs a lode-like character, the garnet becoming a true veinstone, or gangue, for the copper ore (*G*, p. 889).

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
	8. In the Globe Camp, Arizona, "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. Even this alteration is not always recognizable" (*H*, pp. 85–86). (This is rather difficult of explanation on the recrystallization hypothesis, especially as the Globe limestone contains shaly and arenaceous beds.)
18. At San Jose, Tamaulipas, Mexico, diorite-porphyry intrudes Cretaceous limestones and produces garnet zones. Kemp admits that the limestone, although to all appearance pure $CaCO_3$, contains cherty and shaly beds. Analyses show the limestones to contain from 4 to 9 per cent. of insoluble constituents. This is all the recrystallization hypothesis requires (*J*, p. 189).	9. Kemp states that the recrystallization of a limestone would require the production of cavities which in reality are not found. The silicate rock is a fairly dense and solid variety (*J*, p. 202). (The recrystallization takes place under great pressure. This would eliminate cavities.)
19. In J. F. Kemp's article entitled "Copper Deposits at San Jose, Mexico," appears the following statement: "Dr. W. L. Austin has called my attention to a very striking illustration of these relations"	

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(zone of silicates following certain layers) "at Sacrificio Mountain, Nombre de Dios, Durango, Mexico, in which the zones are wollastonite. It would seem from this as if the siliceous beds yielded wollastonite, and the neighboring calcareous beds marble. No doubt these cases strongly favor recrystallization in situ" (*J*, p. 198). 20. In the Elkhorn District, Montana, "the strata about the Black Butte stock dip toward it from all sides, indicating a settling-in of the crust upon the partially cooled and consequently contracted magma" (*K*, p. 444). (This might be due to a contraction of volume on the part of the limestone.) 21. The Keene limestones (Elkhorn) "being less argillaceous than the Starmount limestones, the garnet sinks to a subordinate amount and the siliceous impurities combine with the lime and magnesia, predominantly as a pyroxene and no doubt approaching a pure diopside in composition" (*K*, p. 547). (This shows that the garnet (grossularite) is definitely related to the impurities in the limestone.) 22. Pure limestones in the Elkhorn District, and but four feet from the intrusive granite are con-	

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
verted into "white, coarsely granular marbles, whose only impurities are 5 per cent. of wollastonite in scattered microscopic crystals. . . . The metamorphism in rocks such as the Starmount siliceous and argillaceous limestones is strongly marked for distances of a quarter to half a mile from the intrusions and in a minor degree extends much farther" (*L*, pp. 291–292).	
	10. "Garnet and epidote are not confined to the limestone, but are also abundant when greenstone and gray granite are the country rock" (*M*, p. 63*A*). "Epidote, tremolite, garnet are developed in all the older rocks (granodiorite among the others), and apparently less readily in the limestone than in the other rocks" (*M*, p. 109*A*).
23. "Even the most massive phases of the garnet rock appear in thin section to be made up of an aggregate of fairly well-formed crystals. . . . The iron ore is not intermixed with the garnet. . . . Bodies of yellowish-green garnet in thin section are seen to be an aggregate of more or less idiomorphic crystals of doubly refracting garnet, with angular spaces be-	11. The presence of "quartz-blouts" around the periphery of the porphyry in the Robinson Mining District seems to indicate a transfusion of silica from the intrusive to the limestone (*N*, p. 329). (This phenomenon belongs to a phase of contact action distinctly later than the formation of the "secondary silicate zone.")

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tween the crystals filled with calcite" (*N*, p. 315). Robinson Mining District, Nevada.

24. The secondary silicates, garnet and colorless pyroxene, which are formed in the crystalline limestones of the eastern Adirondacks, are considered by Kemp as formed by dynamic metamorphism. In this process there can be no addition of material (*O*, p. 247).

25. Limestones in the Adirondack region are interlaminated with different varieties of gneiss (garnetiferous and micaceous, pyroxenic and hornblendic). The latter show a great amount of crumpling and crushing, while the former are massive (*P*, p. 265). The evidences of contraction of volume are not preserved in limestone.

26. Garnet and ore have a different time of formation in the Velardeña District, Mexico (*Q*, p. 709).

DIRECT CONTRIBUTION.

12. Spurr and Garrey show in the contact zone at Velardeña, Mexico, a somewhat definite order of deposition of the contact minerals, the later ones *replacing* the earlier ones (*Q*, p. 709).

13. Yung and McCaffery find a very intimate association of chalcopyrite and garnet in the San Pedro District. They are so mixed as to indicate simultaneous formation (*R*, p. 355).

RECRYSTALLIZATION.

27. In the Elkhorn District, Montana, ore occurs in a garnet-diopside stratum (altered limestone), 15 to 18 inches thick, dipping 55° to the east, and carrying gold in bismuthinite and bismuth telluride (tetradymite). This ore stratum is conformable with the adjacent beds, but differs from them in composition. (This selective action of metamorphism must be closely related to the original composition of the stratum.) (*S*, p. 734.)

DIRECT CONTRIBUTION.

14. "In many localities as in the Organ Mountains, and the Tres Hermanas, complete garnetization takes place, the bedding and locally even the fossils being preserved" (*T*, p. 42).

15. Garnet, epidote, augite, anthophyllite are abundantly developed in diabase, where it cuts quartzite, and sparingly in the quartzite (*U*, p. 225). (This seems to indicate that the formation of these silicates was independent of lime-holding sediments.) Harder, however, suggests that probably the quartzite is only a silicified limestone.

16. "The characteristic feature (of contact deposits) is the association of the oxides of iron with

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
	sulphides, a combination practically unknown in fissure-veins" (*V*, p. 717).
	17. In the Seven Devils District, Idaho, diorite cuts limestone. Irregular bodies of bornite, chalcocite, and a little chalcopyrite occur in the limestone, simultaneous in crystallization with garnet, epidote, quartz, calcite and specularite (*V*, p. 722).
28. Iron Springs, Utah: "If SiO_2 and Al_2O_3 have been added from without, it is a remarkable coincidence that they should have been added in so nearly the same proportion as in the fresh rock, especially when it is remembered that their proportion in the fresh limestone is not determined by silicate ratios, but rather by the abundance of chert" (*W*, p. 33).	18. Iron Springs, Utah: On the hypothesis that Al_2O_3 and SiO_2 are not introduced it is necessary to grant the addition of Na_2O and NaCl from the intrusive (*W*, p. 77). NaCl is very commonly carried in magmatic waters (*W*, p. 78).
29. It will be noted that the composition of the altered rock is essentially that of a calcareous residual clay (*W*, p. 33).	19. Iron Springs: Ore-bearing fissures cut the andesite and the limestone, and carry as gangue minerals: apatite, garnet, amphibole, and pyroxene (*W*, pp. 76–78).
30. "In the Iron Springs district the field evidence does not positively prove or disprove important volume change, but there is no apparent field evidence to contradict the evidence for diminution	

RECRYSTALLIZATION.

of volume here calculated. The limestone, though tilted away from the andesite laccoliths, nowhere shows evidence of crumpling or crowding where the bedding can be observed. In the altered phase the bedding has been destroyed, and it is easy to conceive that this structurally amorphous zone may represent only a part of the volume of the original rock, the calcium carbonate having been driven off and the other constituents concentrated. The change in volume of the limestone would scarcely be expected to stand out conspicuously in the field-relations, for it has occurred, if at all, in the band which now does not show original textures or structures, by which change of volume can be measured in crumpling or folding" (*W*, p. 35).

31. Iron Springs: Unaltered Homestake limestone shows on analysis the presence of SiO_2 and Al_2O_3 varying in amount from 4.9 to 10 per cent. (*W*, p. 26). Under the microscope it shows minute grains of calcite, with scattered grains of FeS_2, Fe_3O_4, chert (*W*, p. 25).

32. Iron Springs: "The introduction of ore took place after the development of the silicated contact

DIRECT CONTRIBUTION.

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
phase, as is demonstrated by its occurrence in fissures that intersect this phase" (*W*, p. 27).	
33. Marysville, Mont.: The intruded rocks afford sufficient impurities in the way of SiO_2 and Al_2O_3 to form silicates (*X*, pp. 8–9).	
34. Marysville, Mont.: "The original metamorphism shows no evidence of infiltration, thin concretionary bands of calciate still existing between siliceous bands. Yet calcite, both here and elsewhere, is found to be a mineral which readily suffers change in the presence of siliceous and sulphurous solutions" (*X*, p. 145).	
35. Marysville, Mont.: "In the outer parts of the metamorphic zone a considerable amount of calcareous hornstones and smaller amounts of marble are present, a composition, which, contrasted with that of the inner parts of the zone, is evidence that metamorphism without metasomatic infiltration has been the prevalent process in the outer portions" (*X*, p. 145).	
36. Marysville, Mont.: "These same laminæ of hornstone are formed of diopside, tremolite, actino-	

lite, biotite, muscovite, quartz, and feldspar, and in many places small amounts of calcite. These mineral compositions are such as would result from the simple metamorphism of the Empire and Helena formations, which are of a mixed sedimentary character" (*X*, p. 145).

37. Marysville, Mont.: "In all cases where simple metamorphism and metasomatic infiltration are observed occurring together the latter is seen to take advantage of brecciated or fissile structures, either following the brecciation or accompanying it, but penetrating only slightly into the rock" (*X*, p. 145).

38. Marysville, Mont.: Near Sawmill Gulch, on Silver Creek, a stratum of light-gray diopside hornstone about 50 feet thick may be traced for one-third of a mile. "The dip is less than 10°, and typical Helena limestone is found stratigraphically both above and below. This flat dip and the lack of evidence of direct association with faults, as well as the presence of unmodified rock both above and below, negative the idea that the diopside is here the result of the infiltration of siliceous waters" (*X*, p. 147). (This is directly the opposite of what Lind-

RECRYSTALLIZATION.	DIRECT CONTRIBUTION.
gren finds to be true in the Clifton-Morenci Camp, where the greatest contact effects have been produced in almost pure limestone.)	
39. Ore minerals at limestone-granite contacts are exceptional occurrences. If the ore minerals and the secondary silicates were all magmatic emanations, how can Kemp explain the almost universal presence of the one and the exceptional occurrence of the other? (A. C. Lawson: "Types of Ore-Deposits.—A Review," *Min. and Sc. Press,* Feb. 3, 1912, p. 200.)	

REFERENCES FOR PRECEDING TABLE.

A. J. F. Kemp. Contact-Deposits: Types of Ore Deposits. *Min. and Sc. Press,* 1911.

B. W. O. Crosby. The Limestone-Granite Contact-Deposits of Washington Camp, Arizona. *Trans. A. I. M. E.,* XXXVI., 1905, p. 626.

C. J. F. Kemp and C. G. Gunther. The White Knob Copper Deposits, Mackay, Idaho. *Trans. A. I. M. E.,* XXXVIII., 1907, pp. 269–293.

D. F. L. Ransome. U. S. G. S., Prof. Paper 21 (Bisbee).

E. W. Lindgren. U. S. G. S., Prof. Paper 43 (Clifton-Morenci).

F. George Smith. The Garnet-Formations of the Chillagoe Copper Field, North Queensland, Australia. *Trans. A. I. M. E.,* XXXIV., 1904, p. 467.

G. W. P. Blake. Copper-Ore and Garnet in Association. *Trans. A. I. M. E.,* XXXIV., 1904, p. 886.

H. F. L. Ransome. U. S. G. S., Prof. Paper 12 (Globe, Ariz.).

J. J. F. Kemp. The Copper-Deposits at San Jose, Tamaulipas, Mexico. *Trans. A. I. M. E.,* XXXVI., 1905, p. 178.

K. W. H. Weed and J. Barrell. Geology and Ore Deposits of the Elkhorn Mining District, Jefferson County, Montana. U. S. G. S., 22d Ann. Rept., Part II.

L. J. Barrell. Physical Effects of Contact Metamorphism. *Am. Jour. Sc.,* 1902, p. 279.

M. R. W. Brock. Boundary Creek District, B. C. Summary Reports, Can. Geol. Survey, 1901, p. 51; 1902, p. 92.

N. A. C. Lawson. The Copper Deposits of the Robinson Mining District, Nevada. Univ. Cal., Dept. Geol., *Bull.,* Vol. IV., 1906, p. 287.

O. J. F. Kemp. Rocks of the Eastern Adirondacks. *Bull. Geol. Soc. Am.,* Vol. VI., 1894, p. 241.

P. C. H. Smyth, Jr. Rocks of the Northwestern Adirondack Region. *Bull. Geol. Soc. Am.,* Vol. VI., 1894, p. 263.

Q. J. E. Spurr and G. H. Garrey. The Copper Deposits of the Velardeña District, Durango, Mexico. Econ. Geol., Vol. III., p. 688.

R. M. B. Yung and R. S. McCaffery. The Ore Deposits of the San Pedro District, New Mexico. *Trans. A. I. M. E.,* Vol. XXXIII., 1903, p. 350.

S. W. H. Weed. Ore Deposits near Igneous Contacts. *Trans. A. I. M. E.,* Vol. XXXIII., 1903, p. 715.

T. W. Lindgren, L. C. Graton and C. H. Gordon. The Ore Deposits of New Mexico. U. S. G. S., Prof. Paper 68, 1910.

U. E. C. Harder. The Iron Ores of Western and Central California. U. S. G. S., Bull. 430, 1909, p. 219.

V. W. Lindgren. The Character and Genesis of Certain Contact-Deposits; Genesis of Ore-Deposits, p. 716.

W. C. K. Leith and E. C. Harder. The Iron Ores of the Iron Springs District, Utah. U. S. G. S., Bull. 338.

X. J. Barrell. Geology of the Marysville Mining District, Montana. U. S. G. S., Prof. Paper 57, 1907.

SUMMARY OF CRITERIA.

In the following summary is a tabulation of the chief points favoring one or other of the two hypotheses discussed above. The lists are arranged without reference to the special districts from which the various pieces of evidence are taken. A few suggestions are also offered which are in line with the hypothesis of recrystallization. It must be remembered that the use of the term "secondary silicate zone" is in accordance with the interpretation given on page 14.

A. CRITERIA WHICH FAVOR THE FORMATION OF THE "SECONDARY SILICATE ZONES" BY RECRYSTALLIZATION OF IMPURE LIMESTONES.

1. In every case examined, where detailed descriptions of the intruded strata were given, it was noted that there was a plentiful supply of SiO_2, Al_2O_3, Fe_2O_3, scattered through the rock in the way of quartz, kaolin, and limonite, hematite or pyrite, to afford materials for the formation of the silicates.

2. The natural recrystallizations of impure sediments are almost exactly those that are found at intrusive contacts: Sandstones are altered to quartzites. Shales are altered to epidote-amphibole rocks. Limestones (dolomitic) are altered to iron,—garnet and diopside.

3. Al_2O_3 is practically unknown in igneous emanations.

4. The composite straight-line diagram described in the succeeding section shows a constancy of the $SiO_2:Al_2O_3:Fe(Fe_2O_3)$ ratio throughout the change from fresh to altered rock.

5. The composition of an average sample of the rock from the "contact zone" is practically that of a calcareous residual clay (that is, a limestone after the $CaCO_3$ has been dissolved and carried away).

6. The garnet zones, as described by several of the writers, seem to follow the impure beds in the sediments, independently of the contact.

7. If the silicates were formed by infiltration of material, it would seem a very peculiar feature that just those oxides should be added which are almost invariably present as impurities in any limestone horizon.

8. It would also be exceeedingly peculiar that these oxides should be added in the same ratio as that in which they are to be found in the unaltered limestone series.

9. Masses of marble against the intrusive seem capable of explanation only on the recrystallization hypothesis. It is difficult to conceive of hot siliceous vapors being emitted at the contact with one bed and not with another.

10. There is no reason why the garnet zones should fail, as they do very often, just where SiO_2 and Al_2O_3 are wanting in the limestone.

11. Selective metamorphism on a large scale is a prominent feature of these limestone contacts (see page 30, No. 27).

12. Wherever the garnet masses were examined in thin section under the microscope, it was found that the garnet was present in well-defined crystals, many of them idiomorphic with residuary calcite frequently occupying the interstices. In some cases, the crystals showed double refraction probably due to strain. It seems more probable that these crystals should form by a process of recrystallization after elimination of excess constituents, than by pure replacement (in which the structure and texture of the replaced rock are usually preserved) or by infiltration.

13. The reaction-zones of wollastonite, occurring between nodules of chert and the limestone, found by Crosby in the Washington camp, Arizona, are conclusive proof of the formation of at least some of the silicates by recrystallization without infiltration.

14. Lindgren's failure to find fluid inclusions in the quartz grains of the contact zone, although he found them abundantly in

the quartz of the intrusives, is evidence that at least a different origin must be found for the quartz of the contact zone, from that of the quartz of the igneous rocks.

15. The presence of residuary calcite in the interstices of the garnet crystals is difficult of explanation on the hypothesis of infiltration. If SiO_2 was introduced in gaseous or aqueous form, why did it not unite with this lime, that often occurs very close to the contact, rather than pass it by to seek other lime at a greater distance?

16. Recrystallization into marble and silicates obliterates evidences of volume change. Hence the fact that signs of reduction of volume cannot usually be seen does not argue against recrystallization.

17. A comparison of the "secondary silicate zones" around intrusives with the talcose and serpentinous material formed by shearing in the Randville dolomite of the Menominee region[1] is interesting. In the latter case, there has been an elimination of $CaCO_3$, and a recrystallization under great heat and pressure, in the absence of igneous rocks, of dolomitic limestone to silicates. This is almost exactly the same result as occurs at limestone contacts with intrusives.

18. In all cases of contact metamorphism of limestones the substances *apparently* added by the intrusive are silica, alumina, and iron oxide. The metallic and other constituents which are of undoubted magmatic origin vary widely in character and quantity. Sometimes there is iron, sometimes copper, often both. Again there is gold, silver, manganese. Nickel, titanium, beryllium, boron, fluorine, molybdenum, tin, tungsten, tellurium, etc., occur frequently. It seems rather unusual that the typical pneumatolytic constituents should vary so widely from place to place, while the constituents that go to form the "contact-silicates" should be so uniform, if they are all supposed to have the same origin.

19. In most cases, evidence is sufficient to show that without much doubt, there are two stages in the formation of the lime-

[1] U. S. G. S., Mon. 46, p. 221.

stone contact-zones. This favors the recrystallization rather than the infiltration hypothesis.

20. Advocates of the infiltration theory argue that it is preposterous to demand the reduction of volume required according to the recrystallization hypothesis. On the other hand it is just as improbable that there has been an introduction of such a tremendous amount of material from the intrusive, as is required by those who believe in infiltration.

21. In accordance with the theory of crystallization of a magma the volatile constituents and mineralizers are emitted chiefly while the magma is changing from the liquid to the solid form. If a magma be intruded into a series of impure limestones, at a temperature of 1,000°, for instance, is it not likely that great changes will take place in the composition of the invaded rock, while the intrusive is cooling down to the temperature of crystallization? As a matter of fact, it is a very common occurrence to find pegmatite dikes, aplite dikes, quartz veins ("blouts" of Lawson) cutting across the already formed "contact zone" of silicates. In these dikes and veins, the mineralizers of the intrusive are very largely concentrated.

22. The katamorphism of limestones in the southern Appalachians gives a residual clayey material, but is used as iron ore. The percentages of SiO_2, Al_2O_3, Fe in the fresh limestone are in the same ratio as in the ore material.[1] If anamorphosed, these deposits would give secondary silicates with free iron oxide.

B. CRITERIA WHICH FAVOR THE FORMATION OF THE "SECONDARY SILICATE ZONES" BY INFILTRATION OF MATERIAL.

1. In many cases, garnet masses are found entirely apart from limestones, and apparently connected entirely with intrusive igneous rocks.

2. As a general rule, the literature bears out the statement that basic intrusives do not produce nearly as great a contact zone as acidic ones. Acidic magmas or those high in silica are

[1] R. J. Holden, "The Brown Ores of the New River, Cripple Creek District, Va.," U. S. G. S., Bull. 285.

the rocks generally believed to be most richly provided with the so-called mineralizers.[1] It is an interesting coincidence that cold, basic rocks have been found by Rollin Chamberlin[2] to be the richest in gases.

3. The garnet of the contact zones is in the majority of cases the andradite (calcium-iron) variety. This demands a large amount of iron oxide.

4. A very intimate mixture of chalcopyrite with the silicates in some camps indicates a simultaneous crystallization.

5. In many localities in New Mexico, the bedding and locally the fossils are preserved in garnet.

[1] J. F. Kemp, "Contact Deposits"; see "Types of Ore Deposits," H. F. Bain.

[2] R. Chamberlin, "Gases in Rocks," Publication 106, Carnegie Institute of Washington, 1908.

(To be continued)