

volume; that just enough is introduced in any one place to take the place of that which is left.

5. The reduction in volume required by the recrystallization hypothesis cannot in most cases be disproved. So far as original textures are retained, as they are in some districts, then it is possible to infer, rightly I think, that the volume has not been considerably reduced, and therefore, that elimination has not taken place except by equivalent introduction of new materials. But the supposedly recrystallized substances are usually in a structurally amorphous zone which may well be the residual of an original mass many times greater. Opponents of the recrystallization hypothesis have argued that the necessary elimination of substances, and consequent reduction of volume, is too large to be reasonable. The reasonableness or unreasonableness of this is a difficult point to argue. It is largely a matter of personal opinion. To me it does not seem inherently improbable. Elimination is equally necessary to the alternative hypothesis of introduction of the materials from magmatic sources. Without elimination it is necessary to assume an enormous increase in volume to take care of enough new material to give an average composition of the contact phase.

6. Discrimination of two phases of contact metamorphism is essential to an interpretation of conditions of formation of contact zones.

Students of contact metamorphism may to much advantage study the mathematical theory of heat conduction as applied to an igneous contact. We are indebted to Professors Ingersoll and Zobel for an illuminating discussion of the principles of heat flow from an igneous rock of given dimensions into surrounding limestone. Their conclusions, which seem to be well based on general physical principles, are especially interesting in showing the remarkably slow progress of a heat wave into the limestone. Quoting from Ingersoll's and Zobel's discussion of a hypothetical case:

"The conclusions to be drawn from the curves are: first, that the cooling is a very slow process, occupying tens of thousands of years; second, that the boundary-surface temperature quickly falls to half the initial value and then cools only slowly, and also that for a hundred or more years there is a large temperature gradient over only a few meters and a very slow progress of the heat wave; third, the maximum temperature in the limestone, or the crest (so to speak) of the heat wave, travels outward only a few centimeters a year. The mass behind it will then suffer a contraction as soon as it begins to cool, and the cracking and introduction of mineral-bearing material is doubtless a consequence of this."

Especially significant is the inference from the curves of heat flow that in advance of the heat wave the rock is tending to expand, therefore, to be compressed, whereas, following it during a long period of time there is contraction and the development of cracks. These conditions seem to favor two principal phases of contact metamorphism.

As the igneous mass advances into limestone it presumably is exerting mechanical pressure, judging by deformation at some contacts, and at the same time sending out heat into the surrounding rock, which, itself, increases the pressure. It is difficult to avoid the conclusion that for a time at least the adjacent rocks are under considerable pressure and that this pressure would favor elimination. It does not seem at all necessary or probable that under pressure this elimination should be immediately followed by introduction of

other substances from the magma, or, putting it in another way, that substances from the magma should always so closely follow elimination as to replace molecule by molecule the original materials and thereby prevent any reduction of volume. As the crest of the heat wave advances into the surrounding limestone, lower temperatures follow, with the result that there is contraction and the development of openings. This contraction may effect not only the limestone but the intrusive itself. Into such openings the magmatic solutions may freely enter, and there are deposited the ores and some of their gangue materials. At the same time these solutions may replace the materials of the surrounding rock to a greater or less extent.

That contact metamorphism of limestone has been accomplished in two successive phases has been pretty well proved at certain contacts. It seems probable that when attention is directed specifically to this feature it may be found at others. The first phase seems to be characterized by the production of an amorphous, homogeneous, silicate mass, not definitely associated with fissures. In some cases this is discriminated sharply from, in other cases it merges gradually into, a phase characterized by sulphides and other ore-bearing minerals with their gangue materials, which occur much more largely in fissures. These fissures may often be seen to traverse the silicate zone of the first phase. The minerals of the later phase, both because of their composition and because of evidence of their transportation, cannot be regarded as recrystallizations of materials in place. They afford evidences of introduction from magmatic sources.

The two phases of alteration may merge one into the other both in time and place. The later phase may be expected to obliterate to some extent the earlier phase. Ordinarily the later minerals differ from the earlier ones, but certain silicates, quartz, and other minerals, may be common to both.

I do not attempt to cite evidences in detail from specific localities. My purpose is rather to outline the case for recrystallization. W. L. Uglow, in a recent paper, has cited evidences and references in some detail and in a forthcoming paper will cite more. I do not contend that all contacts will be proved to show important recrystallization or even that all of the illustrations cited in Mr. Uglow's paper are valid ones. I hold only that recrystallization has been proved in enough places and to sufficient degree to warrant its citation as a usual accompaniment of the process of introduction of magmatic materials. In some cases it seems to be important. In others evidence of it is slight or absent, though in these cases it may be masked by the introduction of materials in the second phase of contact metamorphism. Its complete absence in the nature of the case is difficult to prove quantitatively. Advocates of the recrystallization hypothesis have not, so far as I know, held that it was sufficient to explain all contact phenomena. They have offered it only as an explanation of one phase of contact alteration. Failure to consider this hypothesis involves failure to consider the possibilities of a two-phase alteration which seems to me to be the probable key to much contact metamorphism. With the majority of economic geologists, I recognize the conspicuous evidence of the introduction of magmatic materials. My plea is that this hypothesis be not magnified to the exclusion of the recrystallization hypothesis. Quantitative studies of contacts based on adequate sampling have unfortunately been rare. Without them, conclusions can be only qualitative and not exclusive.