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# METAMORPHIC DIFFERENTIATION AT CONTACTS BETWEEN SERPENTINITE AND SILICEOUS COUNTRY ROCKS

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## GEOLOGIC SETTING

Serpentinized ultramafic intrusions are associated with belts of strongly folded geosynclinal sediments in many parts of the world. Commonly these are small lenticular bodies composed largely of serpentine. Lodochnikov[2] has suggested the term "serpentinite" for such intrusions, since the serpentine is considered to be a late stage magmatic mineral of these ultramafic irruptives.

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[1] Chemical analytical work by Phillips; field work and text by Hess.

[2] Lodochnikov, Wartan N., Serpentine and serpentinites and the petrological problems connected with them: *Problems of Soviet Geology*, vol. **2**, no. 5, pp. 119–144, 1933.

In most cases the serpentinites occur by themselves without visible associated mafic rocks. Less commonly they may be associated with, and grade into, mafic irruptives; or in other words mafic irruptives, which may or may not be related to the serpentinites, intrude the same belt. The serpentinite belts of the Appalachians, Alps, Urals, New South Wales, Southern Rhodesia and California are the best known. The intrusion of younger felsic irruptives into the serpentinite belts has been accompanied by abundant hydrothermal solutions. These solutions attack the serpentinites and produce around them a characteristic zonal arrangement of minerals. It is this feature which we have investigated. Near felsic irruptives, under higher temperature conditions, the serpentinite masses are commonly completely enclosed in sheaths of biotite; and farther away from the felsic irruptives, under lower temperature conditions, in sheaths of chlorite. The ultramafic rock within the sheath, and the country rock outside it, show abundant changes.

## METAMORPHIC DIFFERENTIATION

Where two solid rocks are in contact with each other, the one a serpentinite and the other a siliceous sediment or its metamorphosed equivalent, perhaps a quartz-mica schist, there is a strong contrast in chemical compositions. The permeation of hydrothermal solutions along such contacts results in an interchange of material between them as well as the recrystallization of both rocks to form minerals stable under the conditions obtaining. The alterations thus formed on either side of the contact will be called *contact reaction zones.*

In a recent important contribution, Eskola[3] has outlined the principles of metamorphic differentiation and classified them as follows:

(1) Differentiation within a rock mass, due to:
  (a) Growth of crystals or aggregates of crystals (the concretion principle).
  (b) Concentration of the least soluble substances (principle of enrichment in the stablest constituents).
  (c) Extraction and redeposition of the most soluble substances.
(2) Transfer of substances into and from a rock mass, effecting:
  (a) Addition
  (b) Metasomatism
  (c) Extraction of substances

We are inclined to limit the use of the term "metamorphic differentiation" to those cases where redistribution of material already present (class 1 above) is the predominant process, excluding those cases which are largely the result of addition of material, metasomatism or subtraction of material, except where these take place locally within the limited volume under consideration.

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[3] Eskola, Pentti, On the principles of metamorphic differentiation: *Bull. Comm. Geol. Finlande,* no. **97**, pp. 68–77, 1932.

Metamorphosed contacts between serpentinite and siliceous country rock show a marked and striking differentiation, partly as a result of the extreme differences in chemical composition on either side of such contacts and, therefore, afford an excellent example of the process of differentiation for study. The purpose of this paper is threefold: (1) to describe the mineral zones; (2) to present an explanation of their origin; and (3) to inquire into the general process of metamorphic differentiation involved.

## Contact Metamorphic Action of the Ultramafic on its Wall Rock

In order to distinguish between effects produced by original contact metamorphism of the ultramafic intrusive on its wall rock and the later hydrothermal effects which are here under consideration, it was necessary to examine contacts which are free from the younger hydrothermal metamorphism. It was found that the ultramafics produce little or no effect on their wall rocks.[4] In exceptional cases where the ultramafic is very large (dimensions measurable in thousands of feet) some thermal effects may be noted in the country rock.[5] Otherwise contact effects seem to be negligible.

Most of the serpentinites are almost completely serpentinized. If the conclusion[6] is correct, that the water and silica necessary to produce serpentinization are contained within the original magma, then why is it that magma containing perhaps 10 per cent of water has produced so little contact metamorphism on its wall rocks? The explanation may be that if the water is bound in the serpentine molecule during the crystallization of the intrusive, it is not free to migrate and attack the wall rocks. In the case of felsic magmas containing much water, crystallization of anhydrous or nearly anhydrous minerals eventually forces the residual water out of the intrusive and thus accomplishes the characteristic contact metamorphism.

## Conditions Affecting the Metamorphic Differentiation

The chemical environment at the different contacts studied may be considered to be about the same in all cases, in as much as only contacts

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[4] DuRietz, Torsten, also notes lack of contact metamorphism by ultramafics. Peridotites, serpentines, and soapstones of northern Sweden: *Geol. Fören. Förhand.*, vol. **57**, Häfte 2, p. 235, Stockholm, 1935.

[5] H. C. Cooke noted such effects near the large serpentinite mass of Belmina Ridge, Disraeli Quadrangle, Quebec. Report as yet unpublished.

[6] Benson, W. N., The origin of serpentine: *Am. Jour. Sci.* (4), vol. **46**, pp. 693–731, 1918.

Hess, H. H., The problem of serpentinization, etc.: *Econ. Geol.*, vol. **28**, pp. 636–657, 1933.

between serpentinite and siliceous country rock are being considered. The effects of pressure and stress do not seem to be important. The lack of foliation, in general, indicates absence of stress. Temperature would therefore seem to be the chief variable to be considered, and correspondingly higher and lower temperature types are recognized. The lower temperature types will be considered first. The higher temperature types are complex because lower temperature effects have, in all examples studied, been superimposed on them, and thus they cannot be understood until these lower temperature effects are recognized and can be discounted.

## LOWER TEMPERATURE TYPES

The serpentinite occurrences discussed here are from the Appalachian belt, and mostly from the Vermont—Southern Quebec portion of the belt where the exposures may be observed to best advantage. From central Vermont northward along the serpentinite belt through Thetford Mines, all of the occurrences are of the lower temperature type. In the majority of these occurrences the metamorphic differentiation has been so similar that a generalized description will serve to give a picture of the lot.

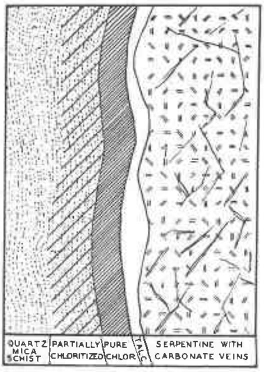

FIG. 1. Lower temperature type of metamorphic differentiation at serpentinite contact with siliceous country rock.

The country rocks are for the most part quartz sericite schists or phyllites. The serpentinite intrusives vary considerably in size and shape. Commonly they are lenticular or pod-like bodies from 50 feet wide by 150 feet long to many times that size. A series of such lenses may coalesce to form a pinching and swelling sheet often more than a mile long. Thick concordant sheets are also occasionally found, as well as irregular stock-like bodies.

Where hydrothermal solutions have attacked the serpentinites (and practically all of the northern Vermont occurrences have been so attacked, as well as most of the ones in Quebec), relations such as those shown in Fig. 1 are commonly observed. A zone of talc from a few inches to several feet wide has developed in the serpentinite parallel to the contact. The schist or phyllite along the contact has been altered to a pure chlorite rock for a foot or more ("blackwall"[7]). The outer margin of the zone of chloritized country rock is occasionally quite sharp, though more commonly it is gradational with chloritization decreasing outward for a number of feet until the normal country rock is again reached. The thickness of both talc and chlorite zones varies considerably, no doubt being dependent on the amount of solutions present during the alteration. An irregular network of magnesite veinlets is found within the serpentinite, and if the talc zone is wide it will usually grade from a pure talc rock near the contact to a mixed talc-magnesite rock ("grit")[7a] farther in.

In some cases, presumably where the temperature was slightly higher at the start of the alteration, sprays of actinolite crystals grew inward from the original contact into the serpentinite for an inch or so. Talc later has replaced the serpentine matrix between the crystals and may occasionally replace the crystals themselves.[8] Less commonly actinolite is found in the chlorite of the chloritized zone. Thin sections of serpentinite-country rock contacts sometimes show a mass of interlocking tremolite or actinolite fibers. Such masses have been called "nephrite." The origin of nephrite deposits has not been clearly understood,[9] but it seems likely that their origin is the same as the coarser actinolites mentioned above.

Thin sections of the chlorite zone show that the rock in most cases consists of 98 per cent or more of a chlorite with only small amounts of accessory minerals. Titanite is the commonest accessory, ilmenite with leucoxene rims is present in some localities, sharp well-formed octahedra of magnetite are common in other localities, a little carbonate may be present, and in a few occurrences epidote is quite abundant. The compositions of the chlorites will be considered later. (Tables 1 and 6.)

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[7] Jacobs, E. C., Talc and talc deposits of Vermont: *Report Vt. State Geol.*, 1913–1914, pp. 382–429, **1914.**

[7a] Jacobs, E. C., *op. cit.*

[8] Hess, H. H., Discussion: On the problem of serpentinization, etc.: *Econ. Geol.*, vol. **30,** pp. 320–325, 1935.

[9] Benson, W. N., *op. cit.*
Preismerk, H., *Schw. Min. u. Pet. Mit.*, vol. **6,** p. 267, 1926.
Kalkowsky, E., *Zeit. D. Geol. Ges.*, **1906.**

*Serpentinite Belt north of Thetford Mines, Quebec*

At the open pit of the Federal Asbestos Mine, 6 miles northeast of Thetford, the footwall contact of a serpentinite sheet, a rolling or undulating surface dipping 30° to 45° to the southeast, has been exposed by quarrying (Fig. 2). A unique feature of this contact is that only a portion of it has been altered to talc and chlorite zones, and the rest remains unchanged. The unaltered contact consists of serpentinite directly against carbonaceous phyllite, which shows no visible contact effects. Note that the serpentinite is an ultramafic rock right to the contact, and no chill facies of less mafic rock is present as might be expected if the serpentinite were considered to be an ultramafic differentiate of a mafic magma. The altered contact shows the typical lower temperature type of metamorphic differentiation described above. The serpentinite has been largely altered to talc for five feet or more from the contact, forming a massive soapstone. The phyllite has been completely changed to a non-foliated pure chlorite rock for a distance of several feet from the contact, where it disappears beneath overburden.

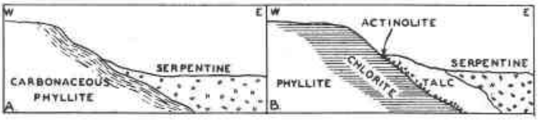

FIG. 2. Relations at Federal Mine in Quebec, showing altered and unaltered contacts.

The distribution of the alterations is not merely haphazard, but seems to be related to steeply pitching undulations of the contact surface in this case. These have controlled the migration of solutions, as shown in the lower part of Fig. 3. As a rule, where particularly broad zones of alteration are found they are usually related to small pitching drag folds involving the contact (upper part of Fig. 3), which have caused a local ponding of solutions. Such a relationship exists at the Kitchener Pit discussed below, and at the East Johnson talc mine, and, in fact, at most places where talc occurs in minable quantities. So common is this type of structure in the Vermont talc mines that the miners refer to the downcurving under side of the drag fold as the "whale belly" and recognize its constant relationship to the talc ore body. In general the lower temperature type of differentiation occurs only on the footwall side of dipping serpentinite sheets and is lacking on the hanging wall side.

For reasons presented above, it can be concluded that the alteration is dependent on migrating hydrothermal solutions—where present the alteration has occurred, and where absent it has not. No other cause satisfactorily accounts for the relations. The abrupt change from altered to unaltered, within a few feet along the strike, eliminates the possibility that the alteration was due to the effects of temperature alone, since such effects would have to be gradational rather than sharply defined. The absence of foliation eliminates the possibility that the distribution of alterations was the result of stress conditions at certain localities along the contact.

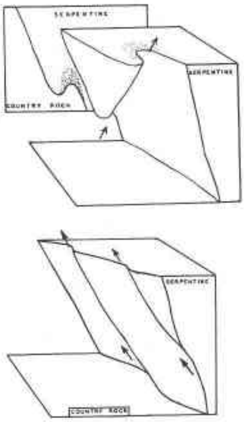

FIG. 3. Structural control of solution migration along serpentinite footwall contacts. Upper diagram shows drag fold control, dotted area represents zone of intense alteration (similar to relations at Kitchener Pit in Quebec and many of the talc mines in the lower temperature portion of the serpentine belt in Vermont). Lower diagram, undulating type of contact (similar to relations at the Federal Mine in Quebec).

Analyses of the phyllite from the Federal Mine and its completely chloritized equivalent are given below. The chloritite contains a little accessory titanite. The distribution of graphite in the phyllite is irregular. It is not known whether the chlorite rock has lost its carbon during the alteration or contained little or no carbon in the first place. For comparison, an analysis of the completely chloritized blackwall from the Bissbee talc mine at the junction of Moretown, Fayston, and Waitsfield, Vermont, is given. The country rock at this locality is a quartz sericite schist similar to the analyzed schist from Roxbury to be described below.

Two and a half miles farther northeast along the same serpentinite belt, a footwall is again exposed at the Kitchener pit in Thetford town-

TABLE 1

| | FEDERAL MINE, QUEBEC | | BISSBEE MINE, VT. |
|---|---|---|---|
| | Unaltered Carbonaceous Phyllite (Q509) | Same completely chloritized (Q545) | Completely chloritized "blackwall" (Vt118) |
| $SiO_2$ | 63.14 | 27.18 | 31.17 |
| $Al_2O_3$ | 16.46 | 18.91 | 14.67 |
| $Fe_2O_3$ | 0.93 | 2.76 | 2.04 |
| FeO | 4.61 | 16.28 | 7.63 |
| MgO | 2.60 | 20.76 | 27.79 |
| CaO | 0.87 | 0.98 | 2.22 |
| $Na_2O$ | 0.55 | 0.38 | 1.04 |
| $K_2O$ | 4.35 | 0.24 | 0.20 |
| $H_2O+$ | 2.82 | 10.55 | 11.02 |
| $H_2O-$ | 0.14 | 0.21 | 0.00 |
| $TiO_2$ | 0.78 | 0.98 | 0.86 |
| $P_2O_5$ | 0.07 | 0.27 | 0.16 |
| MnO | 0.98 | 0.28 | 0.13 |
| $CO_2$ | — | — | 1.41 |
| C | 1.65 | — | — |
| | 99.95 | 99.78 | 100.34 |

Analyses by A. H. Phillips.

Approximate compositions of chlorites calculated from above analyses.

| | (Q545) | (Vt118) |
|---|---|---|
| Ant.* | 25.5 | 48.6 |
| Fe. Ant. | 15.1 | 6.5 |
| At.+(Mg. Cr.) | 45.5 | 39.0 |
| Dn.+(Cr.) | 13.9 | 5.9 |
| | 100.0 | 100.0 |

Optical Properties of Chlorites.

| | | (Q545) | (Vt118) |
|---|---|---|---|
| Indices of Refraction | alpha | 1.6128 ± .0005 | — |
| | beta | — | 1.592 ± .001 |
| | gamma | 1.6148 ± .0005 | — |
| Birefringence | | .002 ± .001 | — |
| Optic Sign | | positive | — |
| Elongation | | negative | — |
| Pleochroism | | $X=Y$ bluish green,<br>$Z$ brownish green to colorless | —<br>— |

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* Molecules as given by Winchell, *Elements of Optical Mineralogy*.

ship, range V, east half of lot 2. Here asbestos veins were traced from unaltered serpentinite into a soapstone near the contact. In the soapstone the asbestos has been replaced by talc, though the cross-fiber structure of the vein remains. From this it may be concluded that the talc and associated minerals were formed after—and probably long after—the solidification of the serpentinite and formation of asbestos veins in it.[10] Thus the talc and associated mineral zones cannot be ascribed to any primary contact metamorphic effect of the ultramafic intrusive on its wall rocks or itself.

Relations similar to those described above, though differing in detail, may be found at the Johnson, Cambridge, Moretown, and Rochester talc deposits in Vermont,[11] as well as many smaller deposits in the same region.

The same lower temperature type of differentiation may be found in the serpentinite belt from southeastern Pennsylvania, across Maryland, and into Fairfax County, Virginia. On the east bank of the Susquehanna, near Pilot at the base of the "State Line Serpentine," a broad zone twenty feet or more wide of completely chloritized country rock occurs, and a large mass of the serpentinite on the other side of the contact is altered to talc. The chloritized rock contains perfect octahedra of magnetite averaging about $\frac{1}{8}$ inch across. The country rock is a quartzose schist with quartz augen, evidently a much sheared conglomerate.

## HIGHER TEMPERATURE TYPES

The higher temperature type of metamorphic differentiation at contacts of the type discussed is characterized by sheaths of biotite instead of chlorite as in the lower temperature type. A zone of biotite (or vermiculite) about one foot thick surrounds the serpentinite lenses or parallels the walls of sheets or dikes. Within this occurs a zone of actinolite several inches thick. The original contact is thought to lie in most cases between the biotite and actinolite zones, for where the differentiation is seen in its incipient stages the amphibolite grows from the contact into the serpentinite. Small lenses of actinolite may also be found in the biotite toward the inner margin. Immediately outside of the biotite zone in the country rock, various combinations of the following minerals are typically found: green hornblende, biotite, albite or oligoclase, clino-

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[10] The relations between serpentinization and formation of talc and associated minerals was discussed at length in another paper. Hess, H. H., *op. cit.*, p. 4.

[11] Gillson, J. L., Origin of Vermont talc deposits: *Econ. Geol.*, vol. **22**, pp. 246–285, 1927. Jacobs, E. C., Talc and talc deposits of Vermont: *Rept. Vt. State Geol.*, 1913–1914, pp. 382–429; and Talc and serpentine deposits of Vermont: *idem*, 1915–1916, pp. 232–280.

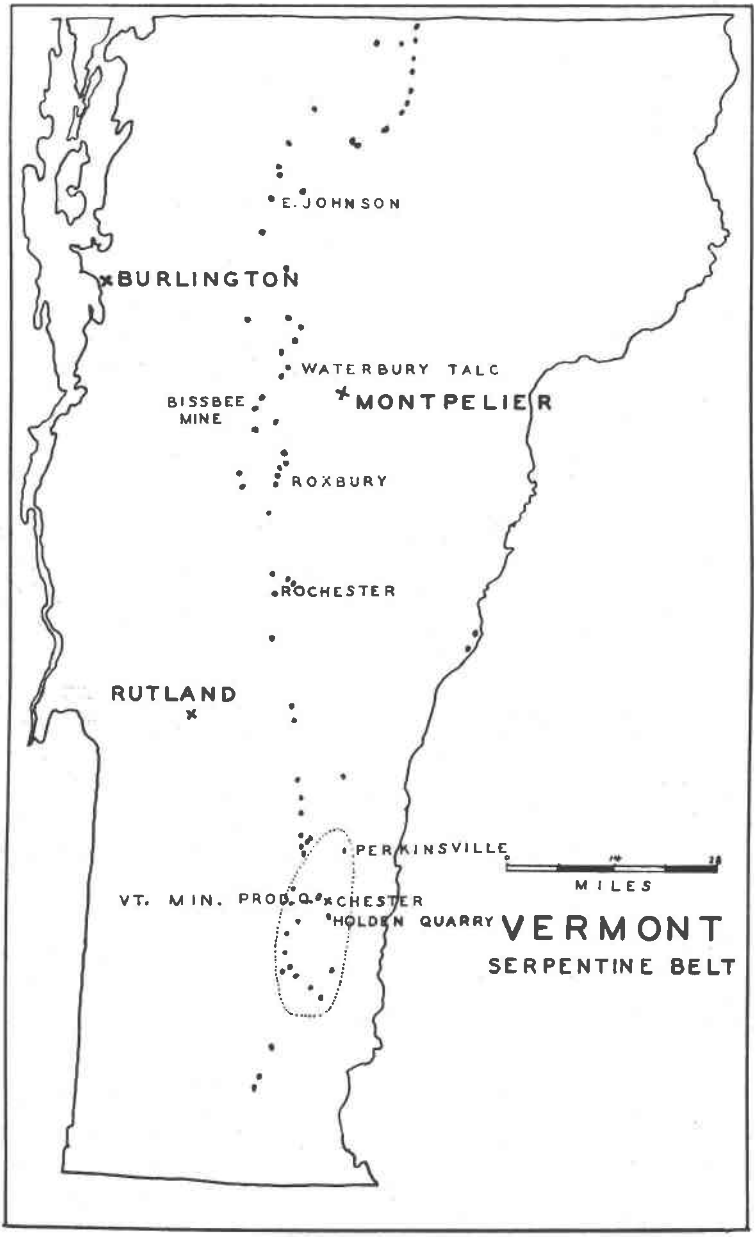

FIG. 4. The black dots represent the serpentinite occurrences. The area enclosed in the dotted oval contains the higher temperature type of metamorphic differentiation at serpentinite contacts as well as a higher degree of metamorphism in the country rocks. The limits of this area are uncertain. It may extend southward into and across Massachusetts. The country rocks of the serpentine belt north of this area generally show a low degree of metamorphism and the serpentinite contacts exhibit the lower temperature type of differentiation, except for a few deposits in the central part of the State where the differentiation is of the intermediate type.

zoisite, epidote, and as accessory minerals either titanite or rutile, and perhaps tourmaline and allanite. Some carbonate may be present, and younger chloritization of some of the ferromagnesian minerals may be noted. Quartz is rarely found in this zone. This rock, rich in ferromagnesian minerals and without quartz, grades outward into the normal country rock gneisses or schists in a few inches. The country rocks usually contain a considerable amount of quartz, plus such minerals as garnet, muscovite, biotite, sodic plagioclase, chlorite, hornblende, and the common accessory minerals apatite, zircon, and titanite.

In most cases, probably very little change takes place within the serpentinite during the higher temperature stage over and above the formation of the actinolite above described. In a few occurrences where the temperature was unusually high a recrystallization of the serpentinite has taken place, forming a rock composed of rosettes of acicular enstatite or anthophyllite crystals. The high temperature effects on the serpentinite are not very clear, however, because almost invariably the whole of the serpentinite has been altered during a subsequent lower temperature stage to a talc or talc-magnesite rock, leaving only a few relics and pseudomorphs from which to reconstruct the sequence of events. During the subsequent lower temperature stage, the biotite of the biotite zone may be replaced by chlorite, and the actinolite to a slight extent by talc. In the chloritized biotite zone there is a strong tendency toward the concentration of $R_2O_3$ oxides. Thus magnetite, and perhaps staurolite, spinel, and corundum in this zone may be ultimate products of intense metamorphic differentiation.

Pegmatites and small felsic intrusions are generally abundant in those areas showing the higher temperature type of metamorphic differentiation and are probably the source of at least a large part of the hydrothermal solutions.

### *Vermont Mineral Products Company Quarry, Chester, Vt.*

At this locality the entire mass of the ultramafic has been changed, and is now mostly a massive talc-magnesite rock. The broader relations are not well exposed since the quarrying is mainly within the talc-magnesite mass. A few large blocks of the contact, however, can be seen, and are most instructive (Fig. 5). The country rock is a muscovite-quartz garnet schist with some chlorite, albite, and rather abundant accessory minerals—pyrite, ilmenite, magnetite, titanite, clinozoisite, rutile, tourmaline, allanite, and several unidentified minerals. As the contact is approached, quartz disappears and plagioclase (oligoclase), biotite, clinozoisite increase notably, as do chlorite and rutile.

This schist abuts against a biotite rock which consists entirely of coarse, unoriented books of biotite. The biotite contains minute inclusions of an epidote mineral, probably allanite, as well as apatite, zircon, and several unidentified minerals. The allanite and zircon inclusions are surrounded by pleochroic halos. The biotite zone is ordinarily about a foot thick, but varies considerably. The original contact probably lies at the junction of the biotite zone with the next zone inward, a band of actinolite rock about 8 inches wide. This band corresponds in position to the incipient actinolite bands found at Roxbury, Vermont, and at the Federal Mine in Quebec, where actinolite needles form at the contact and tend to radiate into the ultrabasic near the contact with the biotite zone. The actinolite is often oriented in a plane parallel to the contact.

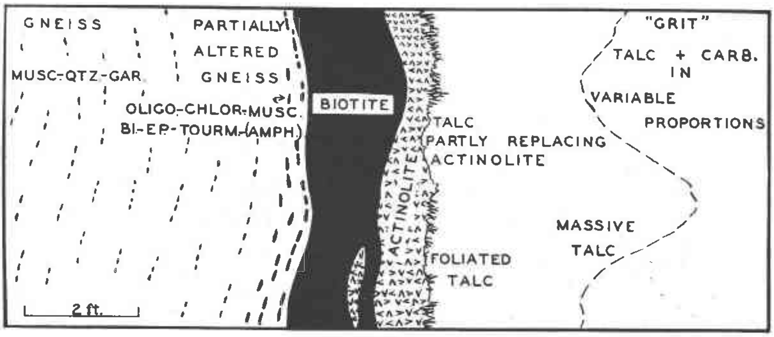

Fig. 5. Higher temperature type of differentiation with lower temperature type superimposed as found at the Vermont Mineral Products Co. quarry, near Chester, Vermont.

At the inner margin of the zone (toward the ultramafic), however, sprays of actinolite needles usually radiate into the talc rock, which forms the next zone. Small, sharply defined lenses of actinolite are occasionally found just within the biotite zone.

Bordering the actinolite is a zone, commonly a number of feet thick, of almost pure talc. In most cases it is distinctly foliated for a foot or more from the contact. The foliation parallels the contact and the foliation planes are complexly crenulated. Delicate actinolite needles extend into the foliated talc and frequently are not broken, although the foliated talc is younger than the actinolite. The extremities of the actinolite needles, projecting into the talc, are in many cases replaced by talc forming perfect pseudomorphs. Occasionally cores of larger, zoned actinolites are replaced selectively by talc, as shown in Fig. 6.

Inside the zone of relatively pure talc lies the altered core of the ultrabasic intrusive, a talc-magnesite rock. Passing across this, the same series of zones as are described above are encountered, but in reverse order as the other contact is approached and passed. The core itself consists of talc and ferro-magnesite in variable proportions, and contains a little disseminated magnetite and chromite.

Black tourmaline (greenish brown in thin section) is common in the schists near the biotite zone, and much tourmaline was found in biotite rock in a "horse" in the soapstone. The biotite itself contains considerable fluorine. Magnetite octahedra, up to $\frac{1}{4}$ inch in diameter, and pyrite cubes, up to $\frac{1}{2}$ inch, replace chlorite of the chlorite zone, and appear to be among the youngest minerals formed. Within the soapstone $CO_2$ has been introduced, and carbonates seem to be the youngest minerals in that zone.

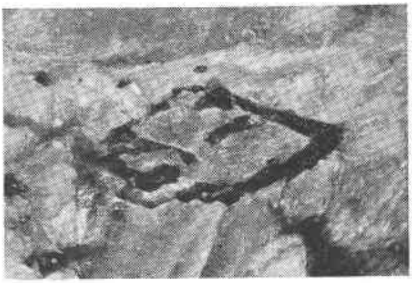

FIG. 6. Actinolite skeleton crystal in talc. Talc has replaced the core of the actinolite crystal which was slightly richer in MgO.

Table 2 gives the chemical compositions of the various zones. The composition of the talc zone, column 6, is an average of several similar rocks from other localities. The mineralogy is so simple that the composition must be fairly close to that of a typical sample of that zone. The serpentinite analysis, column 7, has been estimated from the composition of the talc-magnesite rock by substituting $H_2O$, $SiO_2$, and some MgO for the $CO_2$ of that rock. The resulting estimated composition for the serpentinite is very close to the average of four superior analyses of Massachusetts serpentinites, given in the last column.

### *Holden Soapstone Quarry southeast of Chester*

At this locality the relations are similar to those described above for the Vermont Mineral Products Quarry. A number of small ultramafic

TABLE 2

| | Country Rock, Qtz. Chlor. Gar. Schist | Altered Zone, Ab. Chlor. Clinozo. Schist | Altered Zone, Biotite | Contact | Altered Zone, Actinolite | Altered Zone, Talc (estimated) | Altered Zone, Talc Magnesite | Change 6 to 7 | Serpentinite (estimated from 6) | Average, 4 superior analyses of Mass. Serpentinites |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1. | 2. | 3. | | 4. | 5. | 6. | | 7. | 8. |
| $SiO_2$ | 65.40 | 43.37 | 38.72 | | 53.27 | 60.00 | 31.99 | +8.00 | 39.95 | 39.74 |
| $Al_2O_3$ | 16.82 | 26.10 | 18.39 | | 4.92 | 2.00 | 1.41 | — | 1.41 | 1.14 |
| $Fe_2O_3$ | 0.43 | 2.53 | 1.05 | | 1.43 | 2.00 | 2.24 | — | 2.24 | 3.55 |
| FeO | 6.05 | 5.72 | 9.54 | | 6.78 | 3.00 | 4.30 | — | 4.30 | 3.22 |
| MgO | 2.38 | 4.91 | 18.44 | | 19.47 | 28.00 | 34.31 | +5.00 | 39.31 | 39.35 |
| CaO | 1.78 | 4.66 | trace | | 11.70 | — | 0.51 | — | 0.51 | 0.27 |
| $Na_2O$ | 0.94 | 3.24 | 0.68 | | 0.75 | — | 0.24 | — | 0.24 | 0.08 |
| $K_2O$ | 3.23 | 4.86 | 9.74 | | 0.59 | — | 0.12 | — | 0.12 | 0.07 |
| $H_2O+$ | 1.82 | 3.06 | 0.53 | | 0.39 | 5.00 | 0.93 | +9.50 | 10.43 | 10.85 |
| $H_2O-$ | 0.10 | 0.19 | 0.16 | | 0.05 | — | 0.03 | — | 0.03 | 0.32 |
| $CO_2$ | — | — | — | | — | — | 22.93 | −22.50 | 0.50 | 0.49 |
| $TiO_2$ | 0.59 | 1.02 | 0.47 | | 0.06 | — | 0.00 | — | 0.00 | 0.00 |
| $P_2O_5$ | 0.19 | 0.32 | 0.11 | | 0.11 | — | 0.09 | — | 0.09 | 0.01 |
| MnO | 0.23 | 0.27 | 0.16 | | 0.20 | — | 0.15 | — | 0.15 | 0.05 |
| S | 0.81 | — | — | | — | — | — | — | — | — |
| $Cr_2O_3$ | — | — | — | | — | — | 0.64 | — | 0.64 | 0.32 |
| | 100.25[a] | 100.25 | 97.99[b] | | 99.72 | 100.00 | 99.89 | 0.00 | 99.92 | 99.92[c] |

[a] Less 0.52 O for S.

[b] F present but not determined. A small amount of $CO_2$ is also present.

[c] Includes .11 $FeS_2$ and .35 NiO.

Analyst Nos. 1–6, A. H. Phillips.

No. 8, average of Nos. 1, 4, 5 and 7, Bull. *U.S.G.S.* **579,** p. 158, 1917.

| Modes (vol. %) | 1. | 2.* |
|---|---|---|
| Musc. | 37 | 16 |
| Qtz. | 34 | 0 |
| Garnet | 15 | 0 |
| Chlor. | 5½ | 23 |
| Ab. | 4 | — |
| Oligo. | — | 32 |
| Tit. | 2 | — |
| Ru. | — | .5 |
| Py. | 2.5 | — |
| Tourm. | — | 3.5 |
| Epi. | — | 13 |
| Bi. | — | 12 |

(3) Biotite, alpha = beta = 1.607 ± 001, 2V = 0, Opt. −.

(4) Actinolite, Opt. −, 2V = 84°, alpha = 1.620, gamma = 1.6425, extinction $Z$ to $c = 26°$. $Z$ green, $X = Y$ colorless or pale green.

(6) Ferromagnesite $Sid_{10}Mag_{90}$.

* Values only approximately determined since presence of large, irregularly distributed, crystals make estimation difficult.

lenses (about 12 feet by 40 feet) are found which probably represent sheared apart fragments of a once continuous ultramafic mass. The zonal arrangement of minerals may be seen in Fig. 7. The chief difference between this occurrence and the Mineral Products Quarry is that the ultramafic cores have suffered complete recrystallization to rosettes of acicular enstatite crystals[12] at a high temperature stage previous to their replacement at lower temperature by talc, magnesite, and chlorite. The formation of enstatite probably indicates a higher temperature at the start of the alteration, which caused a breakdown of the serpentine molecule. A higher temperature type of differentiation in also indicated in the country rock by the minerals formed in a zone immediately outside of the biotite zone; namely, blue-green hornblende, brown biotite, oligoclase, a little quartz, epidote, titanite, and apatite. A rock consisting entirely of dark-colored coarse hornblende, which is being replaced by biotite along fractures, was also found. Titanite crystals up to ½ inch long are sometimes found in the fractures at the center of the zone replaced by biotite. It appears as though the crystallization of hornblende may have *begun* before the biotite and is probably contemporaneous with

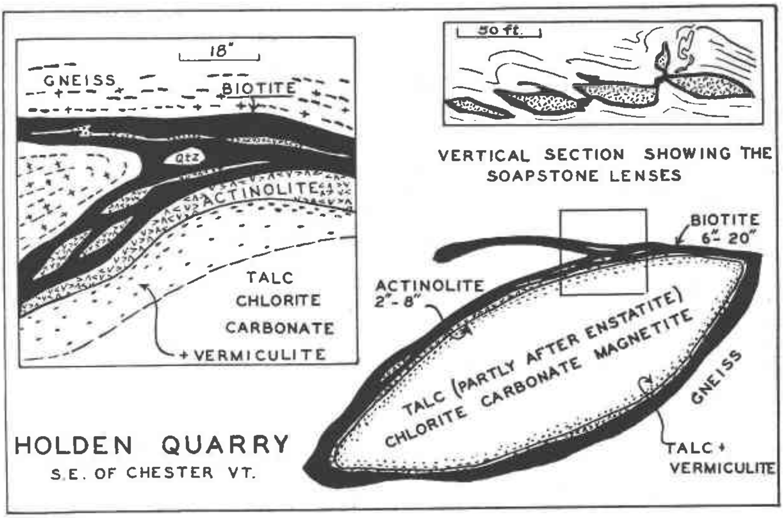

FIG. 7

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[12] Originally thought to be actinolite. Relics have since been found which show that the interior of the lens was once made up of radiate enstatite, and that actinolite only developed along the borders of the lens. Presumably their distribution is controlled by the influx of Ca from the contact. Farther in, in the absence of Ca, enstatite tended to form.

the enstatite crystallization within the ultramafic, thus belonging to the earliest and highest temperature stage, at least in part. Four feet from the contact the country rock is a sodic oligoclase quartz gneiss containing some biotite, epidote minerals, a little muscovite, chlorite, titanite, apatite, and zircon. Many small aplitic and pegmatitic injections invade the country rocks.

Similar mineralogical relations may be noted at the soapstone quarry west of Perkinsville, Vermont, though the exposures are not good.

### *Shetland Islands*

Read[13] has clearly and carefully described zonal arrangements of minerals around ultramafic "balls" or lenses (from a few inches to twenty feet in diameter) which are practically identical with the Vermont higher temperature type of occurrence, the usual sequence of zones being biotite, actinolite, talc and a relic core of antigorite. The biotite may in part be replaced by chlorite, making the sequence biotite, chlorite, actinolite, talc, and antigorite. Read has unravelled a most complex series of events in the history of these deposits, and has drawn conclusions regarding the migration of material in and out of the bodies which are quite similar to those which we have arrived at independently. We cannot agree, however, with Read's idea that "the minerals of the different zones were of simultaneous origin." We believe that a considerable length of time elapsed in every case between the start of metamorphic differentiation at the higher temperature stage and its completion at the lower temperature. In this connection the constant replacement relationship of chlorite to biotite, and talc to actinolite may be pointed out, as well as the fact that talc and chlorite occur in the lower temperature type of deposit independent of any of the higher temperature minerals. Read finds it difficult to explain why actinolite, a higher temperature mineral, should occur between a zone of chlorite and one of talc, both lower temperature minerals, unless they be of simultaneous origin. Our idea of the sequence of events leading up to this relationship is as follows: At the higher temperature stage biotite forms in a narrow zone on the country rock side of the contact, and actinolite in a narrow zone on the serpentinite side. At the lower temperature stage the biotite is partly or wholly replaced by chlorite, while talc replaces the serpentine and perhaps the inner margin of the actinolite zone. Most of the actinolite remains as a relatively stable relic.

We consider that the alterations were produced by slowly migrating or even almost stagnant solutions during changes of temperature that

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[13] Read, H. H., On the zoned associations of antigorite, talc, actinolite, chlorite, and biotite in Unst, Shetland Islands: *Mineral. Mag.*, vol. **33**, pp. 519–540, 1934.

were regional in extent (regional hydrothermal metamorphism). Thus we find a whole area in Vermont in which all of the deposits have suffered the higher temperature type of metamorphic differentiation and the country rocks are of an appropriately high stage of metamorphism, though showing some younger lower temperature effects as well; and another area outside of this in which the metamorphic differentiation at serpentinite contacts is of the lower temperature type and the country rocks show only low temperature metamorphism (Fig. 4).

*Roxbury, Vermont*

This deposit in central Vermont, which is situated geographically between the typical higher temperature and typical lower temperature types of associations described above, shows some features of each type and problably represents intermediate conditions.

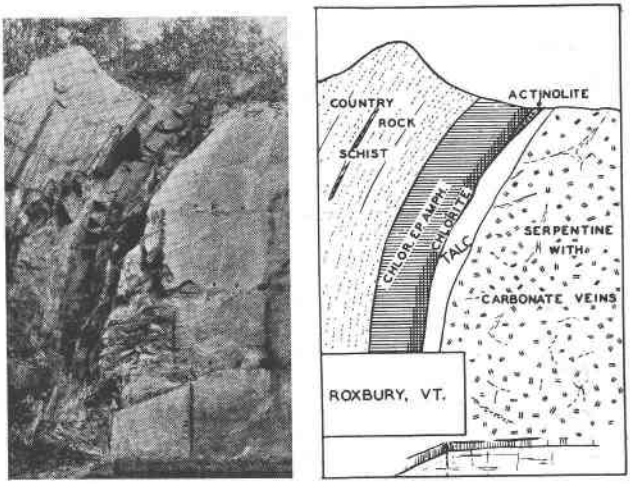

FIG. 8. Verd Antique quarry showing relations interpreted as being intermediate between higher and lower temperature types of metamorphic differentiation as outlined in this paper.

A number of small serpentinite lenses (from 50 feet by 150 feet to three times that size) have been intruded into a uniformly fine-grained quartz sericite schist in the ridge west of the town of Roxbury. The quarrying of these for verd antique has exposed many good sections. Figure 8 shows the relations at one of the quarries. The serpentinite is altered to talc for a few inches from the contact, and actinolite forms small lenses here and there along the contact. The serpentine is cut by a network of carbonate veinlets and carbonate appears along the inner margin of the talc zone replacing the serpentine. The country rock at the contact is a fine-grained, dark green, pure chlorite rock. This rock may show a slight replacement of chlorite by talc at a late stage. A few inches from the contact considerable yellowish green pleochroic epidote appears in the chlorite rock (analyzed rock in table below). A carbonate, fibers of actinolite, and titanite are present in the rock in subordinate amounts. A foot from the contact the rock is albite, epidote, chlorite, actinolite, magnetite schist (minerals in order of abundance) with accessory titanite and apatite and a somewhat coarser grain size. Fifteen inches from the contact the rock is still coarser and consists predominately of epidote, green hornblende, and oligoclase, with minor amounts of titanite and iron ores. At a foot and half from the contact, this rock terminates rather abruptly against but slightly altered country rock, quartz sericite schist. The contact between these two rocks is of the replacement type, and, though commonly parallel to the foliation of the schist, in places it angles across it. The outer part of the zone of altered country rock is quite similar to an equivalent zone at the Holden quarry, which is one of the higher temperature types of deposits. The inner portion of the zone has

TABLE 3

ROXBURY, VT.

| | Qtz. Sericite Schist | Chlor. Ep. Amph. Rock | Original Contact | Talc (estimated) | Serpentinite | Serpentinite |
|---|---|---|---|---|---|---|
| | 1. | 2. | | 3. | 4a. | 4b. |
| $SiO_2$ | 71.10 | 40.55 | | 60.00 | 42.60 | 42.06 |
| $Al_2O_3$ | 12.80 | 14.68 | | 2.0 | 1.22 | 3.25 |
| $Fe_2O_3$ | 2.79 | 5.13 | | 2.0 | 2.86 | 1.60 |
| FeO | 1.77 | 6.79 | | 3.0 | 4.37 | 3.40 |
| MgO | 1.67 | 12.32 | | 28.0 | 36.62 | 38.44 |
| CaO | 1.53 | 10.75 | | — | 1.05 | — |
| $Na_2O$ | 3.46 | 0.59 | | — | — | — |
| $K_2O$ | 2.10 | 0.13 | | — | — | — |
| $H_2O+$ | 1.72 | 5.07 | | 5.0 | 11.37 | 10.94 |
| $H_2O-$ | 0.21 | 0.21 | | — | 0.02 | 0.29 |
| $TiO_2$ | 0.65 | 1.25 | | — | 0.00 | — |
| $P_2O_5$ | 0.12 | — | | — | — | — |
| MnO | 0.09 | 0.14 | | — | 0.21 | 0.30 |
| $CO_2$ | — | 2.08 | | — | — | — |
| | 100.01 | 99.69 | | 100.0 | 100.32 | 100.28 |

Analyses 1 and 2 by A. H. Phillips.
Analyses 4a and 4b by E. C. Jacobs (?).

no doubt been altered at a lower temperature to a predominately chloritic rock, and the total absence of biotite also indicates the lack of complete development of the typical higher temperature stage. The large amount of unreplaced serpentine within the intrusive is similar to the relations found at most of the lower temperature type of occurrences, but the presence of actinolite lenses at the contact indicates somewhat higher temperature conditions than normal for a lower temperature type of association. Thus the conclusion is that this association is intermediate between the two types.

### *Northern Sweden*

DuRietz[14] has presented a wealth of material on the peridotites and their alteration products in this region. The general relations are almost identical with those already described for some of the Vermont-Quebec occurrences. Actinolite, chlorite, talc, and carbonate are the typical minerals formed. Strong tourmalinization very commonly accompanies the alterations. It is limited generally to the outermost zones of alteration and the country rock schists. Some allanite is commonly present. The solutions producing the alterations, in part pneumatolytic but chiefly hydrothermal, seem to have accompanied and succeeded numerous pegmatitic injections. The association of tourmaline, allanite, and pegmatitic injections strongly resembles the associations at the Mineral Products Quarry, Chester, Vermont, though the absence of pure biotite zones and presence of much actinolite and chlorite places the Swedish deposits in a class intermediate between the typical higher temperature and typical lower temperature types, and similar to the Roxbury, Vermont, area.

Some of the amphibolites which DuRietz describes as occurring outside the strongly chloritized zone, between it and the country rock schists, may well be the equivalents of similarly situated amphibolites in some of the Appalachian occurrences. In both regions these amphibolites are characterized by much clinozoisite, or in some cases zoisite or epidote. Tourmaline is much more abundant in the Swedish occurrences. These amphibolites are considered by the writers to be the outermost zone of the metamorphic differentiation and to represent, therefore, altered country rock schist.

DuRietz believes that a large part of the serpentinization is related to hydrothermal solutions from younger felsic intrusives. The writers believe that the bulk of serpentinization is autometamorphic and unrelated to later hydrothermal solutions,[15] thus playing no part in the meta-

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[14] DuRietz, Torsten, Peridotites, serpentines and soapstones of northern Sweden: *Geol. Fören. Förhand.*, vol. **57**, 2, pp. 133–260, Stockholm, 1935.

[15] Hess, H.H., The problem of serpentinization, etc.: *Econ. Geol.*, vol. **28**, pp. 636–657, 1933.

morphic differentiation here under consideration. Perhaps some recrystallization of earlier serpentines to antigorite serpentine during metamorphism may occur, explaining some of the relations observed by DuRietz. It is possible that minute amounts of antigorite might be related to the hydrothermal stage, but if so we are convinced that it is a very small quantity. "Antigorite-like" minerals, such as described by DuRietz, have been noted by Hess[16] in the Schuyler soapstones, and are definitely related to the younger hydrothermal solutions. These are nonpleochroic, pale green to colorless, with somewhat lower birefringence and higher indices of refraction than normal antigorite, and show anomalous blue interference colors. They are considered to be optically negative penninites with a composition of approximately 80 per cent antigorite molecule and 20 per cent of an aluminous chlorite molecule (based on optical properties).

DuRietz gives a large number of chemical analyses of the rocks and minerals, together with splendid descriptions of the individual areas. He recognizes the part played by migration of material in the formation of the mineral zones, though his concept of the migration differs somewhat from that presented by the writers, since he stresses to a greater extent the introduction of material from the pegmatites. As indicated by the abundant tourmaline, introduction of material has played a more important part in the development of the Swedish occurrences than in those of the Appalachians, though redistribution of material already present still seems to be the predominant process.

### *Alps*

A very extensive literature[17] describing the Alpine serpentinites and

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[16] Hess, H. H., Hydrothermal metamorphism of an ultrabasic intrusive at Schuyler, Virginia: *Am. Jour. Sci.*, vol. **26,** 1933. Chlorite "B," Table 4, p. 395.

[17] Ambuhl, E., *Schweiz mineral. petr. Mitt.*, **9,** 1929. Bader, H., *Schweiz. mineral. petr. Mitt.*, **14,** 1934. Ball, J., *diss. Univ. Zurich*, **1897.** Cornelius, H. P., *Neues Jahrb. Min. Geol., Beil. Bd.*, **35,** 1912. Duparc, L., and Mrazec, L., *Bull. soc. Francaise mineral.*, **1893.** Grubenmann, U., *Vierteljahrschr. Naturf. Ges., Zurich*, **53,** 1908. Hezner, L., *Naturf. Ges., Zurich* **54,** 1909. Kundig, E., *Schweiz. mineral. petr. Mitt.*, **6,** 1926. Parker, R. L., *Schweiz. mineral. petr. Mitt.*, **1,** 1921. Prieswerk, H., *Diss. Univ. Basel*, **1901;** *Verhandl. Naturf. Ges., Basel* **15,** 1903; *Schweiz. mineral. petr. Mitt.*, **6,** 1926. Roothan, H. P., *Jahresber. Naturf. Ges., Graub.*, **1919.** Schmidt, C., *Zeitschr. prakt. Geol.*, **1917.** Schneider, A., *diss. Univ. Zurich*, **1912.** Schnell, J. R., *Schweiz. mineral. petr. Mitt.*, **1,** 1926. Schuppi, *Schweiz. mineral. petr. Mitt.*, **1,** 1926. Tarnuzzer, C., *Zeitschr. prakt. Geol.*, **1902;** and *Jahresber. der Naturf. Ges., Graub.*, **1916.** Weinschenk, E., *Abh. ak. der Wiss.* (*math.-phys.*) *Bayern*, **18.** Winterhalter, R. U., *Schweiz. mineral. petr. Mitt.*, **10,** 1930. Chemical analyses compiled in "Chemismus schweizerischen gesteine," *Beitrage zur Geol. der Schweiz.* by P. Niggli, F. de Queroin, R. U. Winterhalter.

their border zones and a great number of chemical analyses are available. In most cases little has been said of the origin of these zones. Where an explanation has been advanced, they have been regarded either as altered mafic border zones of serpentinite (magmatic differentiates of the same magma as the serpentinites) or as the result of contact metamorphism of the serpentinite on its wall rocks and contamination of the border zones of the ultramafic by wall rock assimilation.

## Migration of Elements During Metamorphic Differentiation

### *Stage 1. Higher Temperature Type*

During this stage biotite forms on the country rock side of the contact, and actinolite on the ultramafic side. The schist adjacent to the biotite is also altered somewhat, as is probably the serpentine next to the actinolite, though the latter zone cannot be investigated due to its later complete replacement by talc.

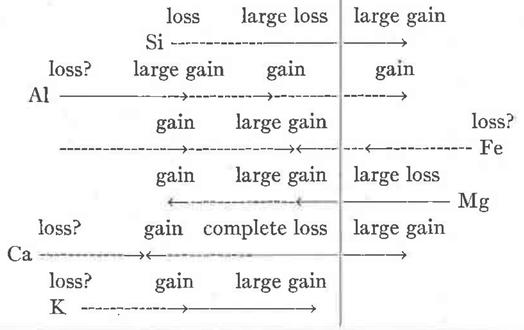
The chemical changes are summed up in Table 4. The replacement of serpentine by actinolite involves a large increase in CaO and $SiO_2$, and a decrease in MgO, and water within this zone. The formation of biotite replacing the schist involves a loss of $SiO_2$ and CaO, a gain in MgO, FeO and $K_2O$, and a slight gain in $Al_2O_3$. The schist adjacent to the biotite zone shows a loss of $SiO_2$ and slight gains in other constituents, judging from the analyses and modes of these zones as given for the Vermont Mineral Products Quarry Table 2. A part of the change in this zone, however, is related to the lower temperature stage.

It may be noted that the unaltered schist contains little plagioclase, whereas the altered schist has a considerable amount (Table 2). This accounts for the increase in $Al_2O_3$ and CaO and decrease in $SiO_2$ in the latter as compared to the former. What little plagioclase there is in the schist is albite, while that of the altered schist is oligoclase. Titanite is present in the schist and rutile in the altered schist. The CaO of the titanite has probably been taken up by plagioclase in the altered rock.

The approximate chemical compositions of the various zones after the higher temperature type of differentiation has taken place are given in the upper part of table 4. The lower part shows the probable migration of each element in the formation of the various zones. It may be seen that the losses and gains from each of the zones tend to counterbalance each other. Quantitative estimates, based on the thicknesses of the zones and the relative amounts of each element lost or gained, though difficult to make, indicate that the losses and gains are of the same order of magnitude.

Table 4

| | | | | CONTACT | | | |
|---|---|---|---|---|---|---|---|
| | 1. Country Rock Unaltered | 1a. | 2. Partly Altered Country Rock | 3. Much Altered Country Rock | 4. Much Altered Serpentinite | 5a. | 5. Serpentinite Unaltered |
| | Musc-Qtz-Gar. Schist | | Oligo-Chlor-Musc-Bio-Clinozo. Schist | Biotite | Actinolite | | Serpentine |
| $SiO_2$ | 65 | — | 44 | 39 | 53 | — | 40 |
| $Al_2O_3$ | 17 | — | 26 | 18 | 5 | — | 1 |
| $Fe_2O_3$–$FeO$ | 7 | — | 8 | 10 | 8 | — | 7 |
| $MgO$ | 2 | — | 5 | 18 | 20 | — | 40 |
| $CaO$ | 2 | — | 5 | 0 | 12 | — | 0 |
| $K_2O$ | 3 | — | 5 | 10 | 0 | — | 0 |



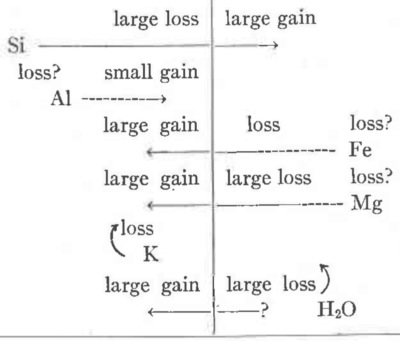
1a and 5a represent slightly altered facies of zones 1 and 5.

### *Stage 2. Lower Temperature Type*

During the lower temperature type of differentiation at serpentine-siliceous country-rock contacts the country rock is typically replaced by chlorite and the ultramafic by talc. In the chlorite zone thus formed, this involves an increase in $MgO$, $FeO$, $H_2O$, and perhaps a slight increase in $Al_2O_3$, and a large loss in $SiO_2$ and alkalies and a small loss in $CaO$. The talc zone represents a gain in $SiO_2$ and losses in $MgO$, $FeO$, and $H_2O$. In this case an interchange of $SiO_2$, $MgO$ and $FeO$ has taken place between the two zones. Alkalies, however, seem to have been carried off by the solutions and lost. Carbonate veins have been formed in the serpentine itself and carbonate may be present in the talc toward the serpentine side of the talc zone. This involves an introduction of $CO_2$ and a loss of $SiO_2$. A small CaO loss from the chlorite zone probably goes into the carbonate. Where only a little carbonate is present it may have a fairly large amount of CaO in it. In those deposits where abundant carbonate is present, it is a ferro-magnesite with very little CaO. Here again it appears that the losses and gains of the various zones approximately balance each other, excepting, of course, $CO_2$-$SiO_2$ interchange and loss of alkalies in the alteration of biotite to chlorite (Table 5).

Table 5

| | CONTACT | | | | | |
|---|---|---|---|---|---|---|
| | 1. Country Rock | 1a. | 2. Altered Zone | 3. Altered Zone | 4a. | 4. Intrusive |
| | Phyllite | | Chlorite Rock | Talc Rock | | Serpentinite |
| $SiO_2$ | 65 | — | 27 | 60 | — | 40 |
| $Al_2O_3$ | 16 | — | 19 | 2 | — | 2 |
| $Fe_2O_3+FeO$ | 6 | — | 19 | 5 | — | 7 |
| MgO | 2 | — | 21 | 28 | — | 40 |
| $K_2O$ | 4 | — | 0 | 0 | — | 0 |
| $H_2O$ | 3 | — | 10 | 5 | — | 11 |



1a and 4a represent slightly altered facies of 1 and 4.

Where the higher temperature type of differentiation has taken place and the lower temperature type has been later superimposed on it, the following events took place (Fig. 9). The biotite, at least in part, and some of the quartz mica schist may become chloritized. The actinolite zone remains for the most part, since it is far less susceptible to replacement by talc than is the adjacent serpentine. It may, however, be partially replaced, forming talc pseudomorphs after actinolite on the inner side (toward the ultramafic) of the actinolite zone. Chloritization of the

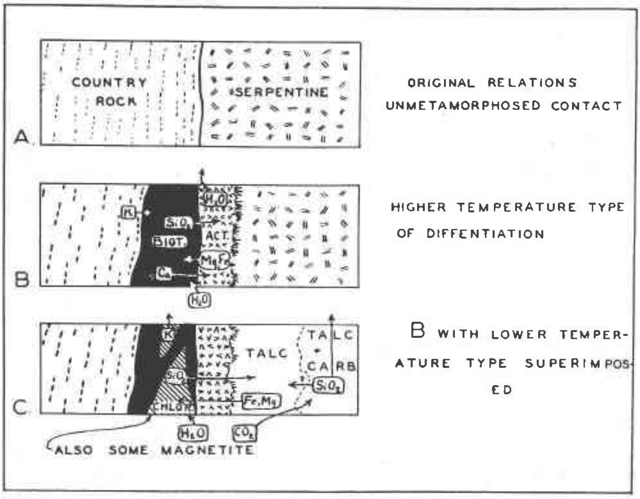
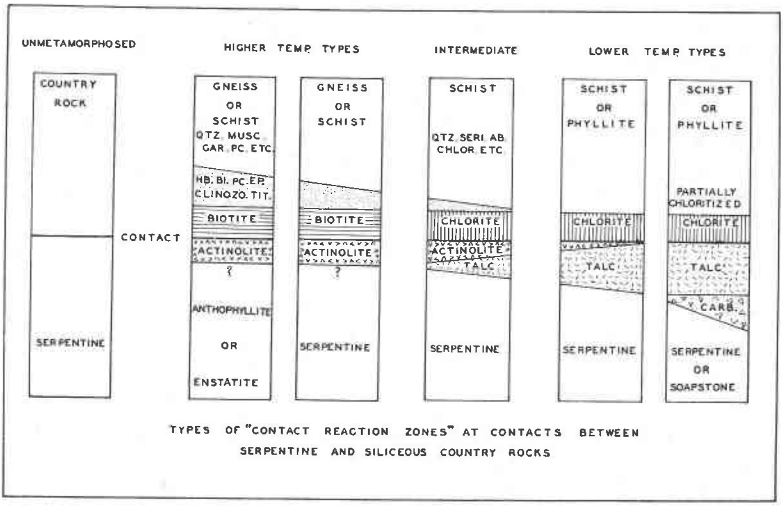


FIG. 9



TYPES OF "CONTACT REACTION ZONES" AT CONTACTS BETWEEN SERPENTINE AND SILICEOUS COUNTRY ROCKS

FIG. 10

biotite zone, a rock already rich in Fe, Mg, and Al, may result in a greater concentration of these elements in the chlorite zone in this type of occurrence than in the type in which the higher temperature typeof differentiation had not taken place. As a result of this concentration of Fe, Mg, and Al, magnetite is commonly developed along with a more Fe and Al-rich chlorite. Corundum and staurolite may be formed under such conditions in this zone, though this point has not yet been investigated (Chester, Mass., emery deposits). As a rule, where the higher temperature type of differentiation has taken place first, the lower temperature type has been much more extensively and vigorously developed than where the lower temperature type occurs alone. This is to be expected, since the higher temperature type occurs closer to the source of the metamorphosing solutions (the felsic intrusives), and these solutions may be expected to be more abundant nearer their source.

## INTRODUCED MATERIAL

Certain constituents in the various localities described above are certainly introduced. For example, on the floor of the Vermont Mineral Products Company quarry at Chester, a tourmaline vein was found cutting a horse of biotitic material. Crystals of tourmaline are also scattered at wide intervals through the surrounding country rocks. At least the boron of the tourmaline must have been introduced. The biotite of the biotite zone at the same locality has an appreciable fluorine content. This also must be introduced. These introductions of boron and fluorine accompanied the higher temperature type of differentiation and may well indicate an early pneumatolytic action as well as hydrothermal.

At a later stage, during the lower temperature type of differentiation, $CO_2$ extensively replaces silica in the ultramafic, and the silica is removed along with much of the water content of the original serpentine. At the same time alkalies are lost from the chlorite zone. In the chlorite zone at the Vermont Mineral Products quarry cubes of pyrite replace chlorite. Pyrite is one of the youngest minerals found at this locality, and indicates that introduction of some sulphur took place toward the end of the lower temperature stage.

It appears that Mg, Fe, Al, and Ca, as well as most of the minor constituents P, Mn, and Ti, are neither introduced nor extracted in important amounts, but rather that they have been redistributed within the limited volume of the rock under consideration. Boron, fluorine, sulphur, and $CO_2$ have been introduced, and silica and alkalies removed by solutions.

## SIMILARITY TO THE CONTACT ZONES OF ALBITITES AND PLUMASITES

Biotite, vermiculite, chlorite, enstatite, actinolite, talc, and corundum are the common minerals formed in alteration zones along the walls of felsic dikes in ultramafics. The dikes themselves are usually altered to albitites and may in some cases contain corundum (plumasite). DuToit,[18] Hall,[19] Gordon,[20] Fersman,[21] and others have attributed the origin of these zones and changes in composition of the dikes to interaction of the felsic *magma* with the wall rocks. Larsen[22] pointed out the quantitative difficulties in the way of such an hypothesis and contended that the alterations were produced by *hydrothermal solutions* which followed the intrusion of the dike. The writers are in accord with Larsen's views.

A strong similarity may be noted between these alteration zones and the ones produced by metamorphic differentiation at contacts between serpentine and siliceous country rocks, when permeated by hydrothermal solutions as described in this paper. In both cases an ultramafic intrusive is in contact with a siliceous rock, and in both cases the alterations are presumably produced by hydrothermal solutions; so it is not surprising that the results are practically identical, even though in the one case (that of the albitites) the solutions are from a source related to one of the two rocks, and in the other case the solutions are from an external, unrelated source.

The extensive albititization of the albitites indicates considerable introduction of soda and probably the extraction of potash, since the biotite present in the contact zones is quantitatively insufficient to account for all of it. Thus in the case of the albitites, the type of contact metamorphism, differs from the metamorphic differentiation described in this paper in that introduction and extraction of material (metasomatism) has been more important.

## CONCLUSIONS CONCERNING METAMORPHIC DIFFERENTIATION AT SERPENTINE-COUNTRY ROCK CONTACTS

1. The process is a general one. Practically identical relations have been noted in widely separated regions, so that no special or complex

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[18] DuToit, Alexander, Plumasite (corundum-aplite) and titaniferous magnetite rocks from Natal: *Trans. Geol. Soc. South Africa*, vol. **21**, pp. 53–73, 1918.

[19] Hall, A. L., Corundum in Northern and Eastern Transvaal: *Union of S. Africa Geol. Surv.*, Mem. **15**, 1920.

[20] Gordon, S. G., Desilicated granitic pegmatites: *Proc. Acad. Nat. Sci. Phila.*, Part **1**, pp. 169–192, 1921.

[21] Fersman, A., Ueber die genesis der Smaragdgruben im Ural: *Compt. Rend. d'Acad. des Sc. de Russia*, pp. 57–60, **1925**.

[22] Larsen, E. S., A hydrothermal origin of corundum and albitite bodies: *Econ. Geol.*, vol. **23**, pp. 398–433, 1928.

series of events can be held to account for the process; but rather the process occurs wherever hot aqueous solutions encounter a contact of this type (serpentine-siliceous country rock).

2. Conditions necessary for metamorphic differentiation of this kind to take place:

   (a) Presence of aqueous solutions—source presumably acid intrusions.
   (b) Elevated temperatures. High enough for the hydrothermal series of minerals to form.
   (c) Serpentine and siliceous country-rock in contact.

3. Minerals are formed during this process in zones which are often monomineralic in composition and generally parallel to the contact. This has taken place by migration of material to and from the zones formed, and to and from adjacent zones of partially altered rock.

4. A subordinate amount of material is brought in by solutions from outside—at higher temperatures boron and fluorine, and at lower temperatures sulphur and $CO_2$. Also at lower temperatures a loss of $SiO_2$ and alkalies occurs.

5. The process of differentiation seems to be as follows: In the presence of aqueous solutions, at a given temperature, a particular mineral—or minerals— (talc for example) is stable in a particular zone or chemical environment (serpentine in this case). Elements not bound in the talc molecule may go into solution, and should they cross the contact may become fixed in a mineral (chlorite) stable in this new chemical environment. Elements bound in the talc will not migrate; and therefore these elements, in the proportion necessary to form talc, will concentrate in this zone (Eskola's "Principle of enrichment in the stablest constituents"). Other elements present, or elements of talc in excess of the proportion necessary to form talc, go into solution ("The solution principle"). Elements which go into solution, and upon migrating across other zones do not become fixed in a stable mineral, may be carried off by the solutions (subtraction); but this is an uncommon occurrence in the cases studied (example: alkalies in the lower temperature type of differentiation). If elements are brought in by the solutions, these elements may also become fixed in a stable mineral in one or more of the zones (addition); (example: boron and fluorine in the higher temperature type of differentiation). Where solutions are bringing in and extracting a large proportion of the elements, the process grades from metamorphic differentiation to metasomatism. (In the case here considered, the amounts of elements introduced and extracted are subordinate to redistribution of material within the limited volume under consideration.)

### TABLE 6

### VARIATION IN COMPOSITION OF THE ROCKS OF THE CHLORITE ZONE.

These rocks are practically monomineralic consisting largely of a chlorite with minor amounts of accessory minerals. Analyses 1, 2, 3, 4, and 10 contain a moderate amount of magnetite. All analyses from references mentioned in text.

| | Graubündens Switzerland | Rischuna Switzerland | Fetlar Shetland Islands | Federal Mine Quebec | Chester Vermont | Williams Mine Vermont | East Johnson Vermont | East Johnson Vermont | Muruhatten Sweden | Gorduno Switerland | Loderio Switzerland | Moretown Vermont | Gorduno Switzerland | Hillswick Scotland | Loderio Switzerland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| $SiO_2$ | 25.56 | 26.82 | 26.85 | 27.18 | 27.07 | 27.10 | 23.67 | 29.34 | 30.58 | 31.02 | 31.12 | 31.17 | 31.70 | 32.55 | 35.91 |
| $Al_2O_3$ | 21.16 | 21.12 | 20.82 | 18.91 | 21.98 | 23.25 | 24.06 | 21.18 | 18.35 | 18.93 | 14.54 | 14.67 | 15.85 | 13.95 | 12.74 |
| $Fe_2O_3$ | 2.88 | 5.07 | 2.34 | 2.76 | 3.40 | 2.25 | 1.01 | 2.33 | 2.00 | 0.97 | 3.35 | 2.04 | 2.20 | 0.97 | 2.09 |
| $FeO$ | 15.09 | 8.89 | 10.75 | 16.28 | 10.74 | 10.48 | 8.63 | 8.93 | 6.31 | 1.63 | 3.41 | 7.63 | 3.67 | 5.26 | 3.31 |
| $MgO$ | 19.35 | 25.39 | 27.05 | 20.76 | 23.37 | 24.00 | 24.11 | 24.58 | 29.91 | 33.78 | 32.26 | 27.79 | 34.11 | 32.79 | 31.63 |
| $CaO$ | 2.55 | 1.36 | tr. | 0.98 | 0.00 | 0.65 | 0.23 | 0.00 | tr. | 0.12 | 1.58 | 2.22 | 0.43 | 0.79 | 3.58 |
| $Na_2O$ | 0.16 | — | — | 0.38 | — | — | — | — | — | — | — | 1.04 | — | 0.06 | — |
| $K_2O$ | 0.19 | 0.96 | — | 0.24 | — | — | — | — | — | — | — | 0.20 | — | 0.48 | — |
| $H_2O+$ | 10.25 | 10.39 | 11.20 | 10.55 | 10.71 | 11.81 | 11.96 | 12.16 | 12.57 | 12.70 | 12.60 | 11.20 | 11.36 | 13.19 | 10.51 |
| $H_2O-$ | 0.06 | 0.06 | 1.00 | 0.21 | 0.39 | 0.35 | 0.25 | 0.03 | 0.30 | 0.63 | 1.35 | 0.00 | — | — | 0.10 |
| $TiO_2$ | 2.19 | 0.19 | — | 0.98 | — | — | — | — | — | tr. | 0.60 | 0.86 | tr. | — | 0.42 |
| $P_2O_5$ | 0.27 | — | tr. | 0.27 | — | — | — | — | — | — | — | 0.16 | — | — | — |
| $MnO$ | 0.14 | 0.04 | 0.18 | 0.23 | 0.31 | 0.47 | 0.51 | 0.67 | 0.04 | — | tr. | 0.13 | — | 0.16 | — |
| S | — | — | — | — | 0.20 | 0.04 | 0.17 | 0.05 | — | — | — | — | — | — | 0.11 |
| $Cr_2O_3$ | — | — | — | — | — | — | — | — | 0.02 | tr. | tr. | — | 1.35 | — | — |
| $CO_2$ | — | — | — | — | — | — | — | — | — | — | — | 1.41 | — | — | — |
| | 99.85 | 100.29 | 100.19 | 99.78 | 98.17 | 100.40 | 99.60 | 99.27 | 100.03 | 99.78 | 100.81 | 100.34 | 100.67 | 100.19 | 100.40 |

After some material has migrated and has become fixed in minerals of a different zone, the chemical composition of that zone has been changed, and thus the minerals stable in this environment may now be somewhat different from what they were when the migration started. Thus a very complex series of shifting equilibria are set up. The composition of the chlorite stable in the chlorite zone, for example, is probably continually shifting as the differentiation proceeds, and the chemical composition of this zone and of the solutions entering it are changing. Note the variation in composition of the rocks of the chlorite zone thus formed (Table 6).

As enrichment of the chlorite zone in iron and alumina takes place, new minerals, magnetite and perhaps staurolite and corundum, become stable, along with a chlorite rich in $R_2O_3$ oxides. The relative proportions of these minerals, as well as the composition of the chlorite, may vary as differentiation proceeds. So many variables are difficult to comprehend, though many arrested stages of the process may be examined and the results tabulated in such a form that the general process may thus be outlined in simple terms.

Still another important variable may be introduced—temperature. The examples used above deal mostly with the lower temperature type of differentiation, a differentiation that proceeded largely as the result of self-induced changes in chemical environment, without much change of temperature. It is difficult to tell, however, which changes should be ascribed to the above cause and which to temperature variation, since both were no doubt operative. Thus the elements fixed in stable minerals in the various zones, as well as the elements going into solution in the various zones, will vary with temperature. So it is entirely possible for an element to be fixed in one zone at one temperature and migrate out of that zone at another temperature (example: potassium migrates into the biotite zone; but as the temperature becomes lower, chlorite becomes the stable mineral in this zone and potassium is no longer fixed in a stable mineral so that it migrates out of the zone).

6. In conclusion, the writers wish to point out that only those localities showing the most ideal relations have been described in this paper. In a large proportion of cases examined in the field complex relations were found. Drag folds, faults, shear zones, and other irregularities may control migration of solutions in the differentiation and as a result the zones developed may depart widely from being parallel to the contact; repetition of zones may be found; biotite, actinolite, chlorite, talc, etc. veins may cross-cut certain zones, and infolded wall rocks and xenoliths of wall rocks may cause repetitions of certain zones within the ultramafic.

Post differentiation deformation may, of course, also greatly disturb relations.[23]

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[23] Prof. A. F. Buddington pointed out to the writers the analogy between the contact reaction zones around serpentinites (macro-coronas) and certain micro-corona structures occasionally found around olivines in gabbros and norites. The micro-coronas are generally considered to be formed by deuteric solutions without change in the bulk chemical composition of the enclosing rock. This is interesting, since the writers have proposed that the much larger scale contact reaction zones also have been formed largely by rearrangement of materials already present.