SUOMEN GEOLOGINEN TOIMIKUNTA
GEOLOGISKA KOMMISSIONEN I FINLAND

# BULLETIN
DE LA
# COMMISSION GÉOLOGIQUE
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N:o 103

SUOMEN GEOLOGISEN SEURAN JULKAISUJA
MEDDELANDEN FRÅN GEOLOGISKA SÄLLSKAPET I FINLAND
COMPTES RENDUS DE LA SOCIÉTÉ GÉOLOGIQUE DE FINLANDE

VII

AVEC 2 FIGURES DANS LE TEXTE

HELSINKI — HELSINGFORS
AOÛT 1933

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## SISÄLLYSLUETTELO. — INNEHÅLLSFÖRTECKNING. — SOMMAIRE.

# KIRJOITUKSIA. — UPPSATSER. — ARTICLES

1.

# EIN WORT ZUR MIKROTEKTONIK BESONDERS IM ARCHÄISCHEN GRUNDGEBIRGE.

Von

TH. G. SAHLSTEIN.

INHALTSVERZEICHNIS.



## VORWORT.

Die tektonische Untersuchung des finnischen archäischen Grundgebirges, die neuerdlings auf die Anregung von Wegmann (1928; 1929) in grösserem Umfange betrieben worden ist, hat in den letzten Jahren viele fruchtbare Resultate über die Struktur und Bewegungen unseres Gesteinsgrundes zu Tage gebracht. Wie z. B. die schönen Arbeiten Sakselas (1932; 1933) zeigen, bietet besonders das Studium der Axialverhältnisse wichtige Anhaltspunkte bei der Lösung tektonischer Fragen aller Art und scheint hier gleich grosse Bedeutung zu besitzen, wie in den jüngeren Faltunszonen. Es ist wohl als sicher anzunehmen, dass wir, im Gegensatz zu den früheren Ansichten, im

Archäicum weite Areale vor uns haben, wo die Anatomie des Gesteinsgrundes weitgehende, obschon nicht vollkommene Analogien mit der alpinen Deckentektonik zeigt und offenbar ähnliche Bewegungsbilder vorweist. Es ist aber ebenfalls als sicher anzusehen, dass wir im Archäicum auch mit Formationen zu tun haben, deren Deformationen unter abweichenden Bedingungen vor sich gegangen sind und die demzufolge anderartige strukturelle Züge erkennen lassen. Diese echte Grundgebirgstektonik unterscheidet sich streng von der alpinen Deckentektonik und stellt zum grössten Teil eine Folge des ihr zukommenden tieferen Niveaus dar.

Weil nun im Archäicum z. T. ein der alpinen Tektonik fremder Charakter vorherscht, ist es von voraus nicht für selbstverständlich zu halten, dass die tektonischen Elemente, die man im Felde beobachtet und notiert, immer identisch mit derjenigen der Alpen seien. Es k ö n n e n die Streckung, Schieferung usf. genau diegleiche Genesis zeigen, durch die gewöhnlich in den jüngeren Formationen ähnliche Parallelstrukturen ausgearbeitet und weiterentwickelt werden, es ist aber sehr wohl denkbar, dass es auch Fälle gibt, wo die Beziehung der Regelung zu der megaskopisch sichtbaren Parallelstruktur eine a n d e r e ist.

Um diese Tatsache hervorzuheben, hat der Verf. bei dieser Gelegenheit das Wort nehmen und darauf hinweisen wollen, dass eine gefügeanalytische Untersuchung bei Seite megatektonischer Arbeiten von grösster Wichtigkeit ist zur richtigen Beurteilung der im Felde beobachteten tektonischen Elemente. Weil z. T. noch die megatektonische und besonders aber die gefügeanalytische Bearbeitung unseres Archäicums erst im Anfange steht, können zur Zeit keine allgemeingültige Schlüsse von der eventuellen Eigenart der archäischen Grundgebirgstektonik in sowohl Mikro- als Megadimensionen gezogen werden und das ist auch nicht die Absicht dieser kleinen Arbeit. Es wird nur versucht, mit einigen Beispielen aus der Literatur sowie aus eigenen Untersuchungen zu zeigen, wie wünschenswert es wäre, dass man auch in unserem Archäicum die Mikro- und Megatektonik Hand in Hand weiter entwickelt und einander stützen lässt.

## DIFFERENTIALBEWEGUNGEN IM FINNISCHEN ARCHÄICUM.

Als Resultat seiner während einer Reise in Finnland gemachten Beobachtungen ist Sander (1914) zu der Auffassung gelangt, »dass man (in Finnland) im Lande der Ausnahmen steht von der grossen Regel, dass kristalline Schiefer Korn für Korn durchbewegte tektonische Fazies sind». Zu diesen Ausnahmen gehören nach ihm zum grössten Teil die bottnischen Schiefer in der Gegend von Tampere, in denen »die Bewegungen durch Verschiebung grosser Elemente ohne Differentialbewegung in deren Gefüge» erfolgten und in denen die Regelung von Quarz und Glimmer, die später von Sander (1928) an einem Beispiel untersucht worden ist, z. T. eine Folge der reinen Abbildungskristallisation vorgefundener sedimentärer Gefüge, z. T. aber diejenige der Kristallisationsschieferung darstellt. Dazu hat er doch auch echte Tektonite oder »Gesteine mit summierbarer Teilbewegung im Gefüge» im Orijärvigebiet, in der karelischen Schieferformation etc. vorgefunden und zur Seite der alpinen tektonischen Fazies gestellt.

In neuerer Zeit haben sich bei uns besonders Wegmann und Kranck (1931) sowie letzthin Kranck (1933) mit der Kinetik der Deformationen im archäischen Grundgebirge beschäftigt und zwar in den Migmatitgebieten südfinnischer Schären, wo die herrlichen Aufschlüsse eine ausgezeichnete Gelegenheit für das Studium der Injektion sowie der Tektonik darbieten. Diese beiden Autoren haben in ihrem Untersuchungsgebiete das Zustandekommen der Parallelstruktur durch Annahme kräftiger Differentialbewegungen und nicht durch die Kristallisationsschieferung im Sinne von Becke (1924) erklärt. Sie haben in der Deformation viele zeitlich getrennte Phasen unterschieden, wobei die Gesteine in den älteren Phasen »im alpinen Stile horizontalüberschoben und einscharig (im Sinne von Schmidt, 1932) deformiert» (Kranck), in den späteren Phasen aber durch Intrusion jüngerer Granite stark umkristallisiert, mit steileren Scherflächen in einem tieferen Niveau durchsetzt und schliesslich mylonitisiert wurden.

Diese kinetische Betrachtungsweise, die sich als Gegensatz der von vielen Autoren noch heute vertretenen statischen Anschauung stellt, gelangte in der früheren geologischen Literatur in Fennoskandia öftens nicht zur Geltung, ich glaube aber, man schlägt kaum fehl, wenn man sagt, dass man bei uns immer mehr geneigt ist, die Kinetik bei der Deformation als Teilbewegung in der Schieferungsebene zu deuten und nicht als Kristallisationschieferung.

## BEZIEHUNG ZWISCHEN MIKRO- UND MEGATEKTONIK.

Eine der wichtigsten Aufgaben bei den regional-geologischen Gefügeuntersuchungen ist die Klarlegung der Beziehung zwischen Mikro- und Megatektonik, die auf Grund naturorientierter Gefügediagrammen auszuführen ist. Die Parallelität der Struktur in diesen beiden Dimensionen, wenn sie überhaupt auf denselben Beanspruchungsplan zurückgehen, ist durchaus zu erwarten und ist auch in der Tat in zahlreichen Fällen beobachtet (D. Korn 1928, L. Korn 1930, Johs 1932, etc.). Die Gesteine sind dabei oft typische Gürteltektonite mit einem deutlichen Eingürtelbild (Sander 1928), und der Pol dieses Gürtels, die eine Schnittgerade der Scherflächen darstellt, stimmt unter Erhaltung monokliner Symmetrie mit der megaskopischen Streckung bezw. Striemung vollkommen überein. Es ist aber auch zu erwarten und ebenfalls erwiesen worden (z. B. Drescher 1932), dass die Mikrotektonik, die sich in der Regelung von Quarz etc. spiegelt, lokal nicht mit den megatektonischen Elementen zusammenfällt, sondern auf ein ungleichufriges Strömungsbild hindeutet, dass aber diese Durchkreuzung der Mikro- und Megatektonik über weite Areale sogar die Regel vorstellt, ist, soweit ich weiss, bisher nur in einem Teil der lappländischen Granulitformation beobachtet (Sahlstein 1933) und wird noch weiter unten in einem besonderen Kapitel erörtert.

## SYMMETRIE DER GESTEINSDEFORMATION.

Die Symmetrie einer tektonischen Bewegung, wie sie von der gefügeanalytischen Schule aufgefasst wird, stellt einen Begriff dar, der ohne Zweifel dem Tektoniker in vielen Problemen aller Dimensionen tüchtig zur Hilfe stehen kann, denn nach dem allgemeingültigen Gesetz von der Korrelation der Differentialbewegungen mit dem grosstektonischen Strömungsbild lässt sich oft auf Grund mikrotektonischer Symmetrie wichtige Schlüsse von den Symmetrieverhältnissen grosstektonischer Bewegungen ziehen. Man kann, wie Sander (1930) ausführlich dargelegt, in der passiven (Rüger 1931) Gesteinsdeformation verschiedene Symmetrieklassen unterscheiden, die alle ihre eigenen Entstehungsbedingungen voraussetzen und etwa wie folgt eingeteilt werden können:

Die statistisch i s o t r o p e Symmetrie, wo das Gestein gänzlich ungeregelt erscheint, entsteht immer in einem unbewegten Zustande und gehört also nicht zu den echten Tektonitsymmetrien.

Die W i r t e l s y m m e t r i e, die die Symmetrie eines Rotationsellipsoids, sowie die r h o m b i s c h e Symmetrie, die diejenige eines dreiachsigen Ellipsoids besitzt, sind in der Natur nur ausnahmsweise verwirklicht und entstehen unter einer einfachen Beanspruchung, von Becker (1893) »simple strain» benannt.

Die m o n o k l i n e Symmetrie stellt die wichtigste und sicherlich die am weitesten verbreitete Symmetrieklasse der Gesteinsdeformation dar und ist überhaupt jedem ungestörten Bewegungsbild als normal zu betrachten. Die einzige vorhandene Symmetrieebene fällt mit der Deformationsrichtung zusammen und steht senkrecht zur Schieferung.

Die trikline Symmetrie, die neben der monoklinen ebenfalls eine äusserst weite Verbreitung in der Natur aufweist, ist oft im Gesteinsgefüge ohne irgendwelche äussere Merkmale vorhanden und lässt sich nur aus der resp. Regelung herauslesen. Sie steht gewissermassen hinsichtlich ihrer Entstehungsbedingungen in naher Beziehung zu der monoklinen Symmetrieklasse und tritt in den Stellen einer monoklin deformierten Masse vor, wo die äusseren Widerstände lokale Störungen mit unregelmässigen »Wirbeln» im Gesteinsfliessen verursachen.

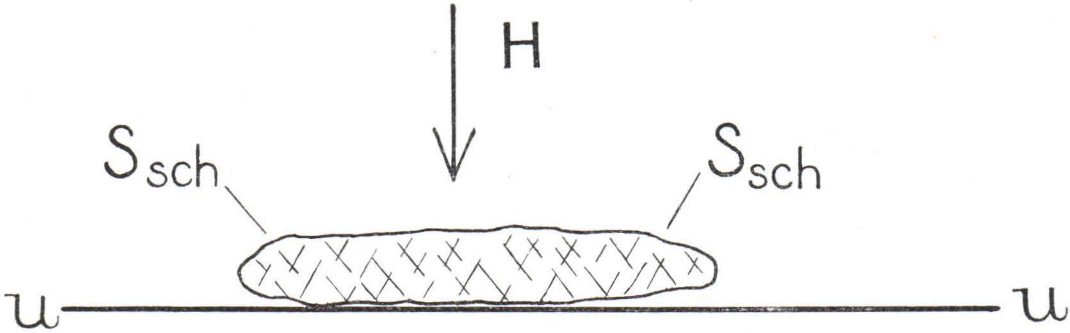


Fig. 1.

## ENTSTEHUNG DER SCHIEFERUNG DURCH PLÄTTUNG.

Neben der von Becker (1893) und später von Schmidt (1925; 1932) in schärferer Form gegebenen Erklärung, nach dem die Schieferung in überwiegend meisten Fällen als eine Folge der Teilbewegung in der Schieferungsebene (Scherungsschieferung) gedeutet wird, und unter voller Zuerkennung ihrer Wichtigkeit betont Sander (1930) noch eine andere Art der Entstehung einer flächenhaften Parallelstruktur, die in diesem Zusammenhange von besonderer Interesse ist. Er betrachtet der Einfachheit halber einen unrotationalen Strain, macht aber dabei darauf aufmerksam, dass nichts verändert wird, wenn man einen rotationalen Strain mit schiefer Pressung auf die analoge Weise vor sich denkt. Eine Gesteinsmasse (Fig. 1), die senkrecht zum Hauptdruck H gegen die fest gedachte Unterlage U—U gepresst wird, erleidet infolge der in Tätigkeit getretenen Scherflächen $S_{sch}$ eine parallel mit der Unterlage laufende Plättung, die sich in einer megaskopischen Schieferung äussert (Plättungsschieferung). Die Regelung, die sich nach den Scherflächen einordnet, fällt hier nicht mit der Schieferung zusammen, sondern zeigt oft besonders bei einem rotationalen Strain einen triklinen Charakter im abc-Achsenkreuz und es stellt sich dabei eine zur Zeit noch nicht zu antwortende Frage heraus, ob nicht wenigstens für die meisten triklin geregelten Tektonite überhaupt eine Erklärung der Schieferung als Plättungsschieferung gerechtfertigt ist.

## STRUKTUR LAPPLÄNDISCHER GRANULITE.

Die Struktur lappländischer Granulite, die vom Verf. untersucht und in einer kurzen perliminären Mitteilung (1933) dargelgt worden ist, zeigt, wie schon erörtert, deutliche trikline Züge, die sogar besonders in gewissen Teilen der betr. Formation einen regionalen Charakter zu besitzen scheinen. Der Quarz, der ziemlich allgemein nach einem Zweigürtelbild geregelt ist, stimmt i. T. mit den von Sander (1930) gefundenen Regelungsbildern sächsischer Granulite überein, zeigt aber doch oft eine niedrigere Gefügesymmetrie. Der Umstand, dass sich der Glimmer in seiner stets scharfen Regelung nie in den untersuchten Fällen der triklinen Stellung des Zweigürtelbildes von Quarz im abc-Achsenkreuz anpasst, sondern immer ein starkes Maximum um den Schieferungspol und eventuell dazu einen ac-Gürtel besitzt, weist vielleicht darauf hin, dass die Regelung von Glimmer überhaupt nichts mit den Bewegungen zu tun hat und bloss eine postdeformatorische Abbildungsschieferung darstellt. Wohl kann man dagegen der Regelung von Quarz eine kinetische Genesis zuschenken und durch eine parakristalline Durchbewegung erklären.

Das flächenhafte Parallelgefüge in der Granulitformation, die sehr oft und teilweise sogar in der Regel nicht mit der Quarzregelung zusammenfällt, ist wohl zum grossen Teil nicht als Scherungsschieferung zu deuten, sondern als eine mit dem Begriffe der Plättungsschieferung vergleichbare Parallelstruktur zu betrachten. Es ist klar, dass man hier und überhaupt in allen analogen Fällen mit der megaskopischen Ausmessung von Schieferung und Streckung die wahren Bewegungen nicht ergründen kann, sondern man ist gezwungen, sich besonders bei allen triklin deformierten Gesteinen der gefügeanalytischen Methode zu bedienen. Durch megaskopische Feldbeobachtungen kann man zwar die b-Achse, mag es auch Streckung oder Striemung sein, bestimmen, was aber diese b-Achse an und für sich bedeutet, das ist nur mittels einer Gefügeanalyse zu entscheiden.

Es muss noch zur Zeit der Zukunft die Frage überlassen werden, in welchem Masse die trikline Gefügesymmetrie im archäischen Grundgebirge vorkommt; jedenfalls scheint es wohl nicht ausgeschlossen, dass wir auch ausserhalb der lappländischen Granulitformation eine Mikrotektonik treffen werden, die nicht mit der entsprechenden Grosstektonik übereinstimmt, sondern mehr oder weniger von ihr abweicht.

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## 2.

# ON THE DIFFERENTIAL ANATEXIS OF ROCKS.

By

PENTTI ESKOLA.

In a recent paper the writer[1] presented the theory that granitic magmas have come into existence mainly by two different processes: 1) crystallization differentiation and squeezing out of the residual liquid from a primary magma which has probably been originally in a varying degree more acid than the average of plateau basalts, and, 2) by differential (partial) re-fusion, or anatexis (a term first proposed by Sederholm), and squeezing out of the re-fused liquid from older rocks that were heated in one way or another above the melting temperature of the lowest-melting portion of the rock mass mixed with water or other mineralizers. Just as granitic magma is the last residual solution in differentiation crystallization of other silicate magmas, just so the first portion to re-fuse of any ordinary silicate rock would have the composition of a granite magma. The down-pressing of rock masses during mountain folding in the orogenic zones was considered to be the most common cause of such re-heating. An intergranular liquid would be formed which would be squeezed out along the shear planes of the rocks during the shearing and rolling movements and, once mobilized, would migrate shorter or longer distances, giving rise to either narrow pegmatitic veins or lenses of migmatites, or to huge masses of granite, of even batholithic dimensions.

The experimental investigation of Goranson[2] on the melting of granite has since brought forth weighty evidence in favour of the hypothesis of partial anatexis by showing that there is a rather sharp break in the crystallization between the last residual »pegmatitic» silicate magma and the diluted aqueous solution which remains after

[1] PENTTI ESKOLA, »On the origin of granitic magmas». Min. und Petr. Mitt., Bd. XLII, 1932, pp. 455—81.

[2] R. W. GORANSON, »Some notes on the melting of granite». Am. J. Sci. XXIII, 1932.

the crystallization of the silicates containing little but silicic acid. This result seems to justify the conception of pegmatitic veins of the venitic adergneisses being crystallizations from magmatic solutions leached out from the rock rather than simple products of an »ultra-metamorphism» (Holmquist), and harmonizes well with the generally observed fact that pegmatites are rather sharply separated from quartz veins in nature, the adularia druses and related low temperature crystallizations being also accompanied by quarz in quantities manifolded in proportion to the feldspars. It is thus possible to form a somewhat more concise idea of what may be accounted for by differential anatexis in areas where granites occur, and of the origin of granitic magmas in general. This is the main theme of this paper.

Many American petrographers, especially Schaller, Hess, and Landes,[1] have been led to the conclusion that replacement has played a very considerable rôle in the genesis of pegmatites, explaining even intergrowths like the graphic feldspar as replacement products. In the opinion of the present writer the replacement hypothesis, applied in such an extension, is exaggerated, although it is no doubt right as far as many of the so-called rare pegmatite minerals are concerned. Even the advocates of this theory admit the existence of »simple» pegmatites which are of a truly magmatic origin without any later hydrothermal replacement. As remarked by Landes, the pegmatitic veins in injected rocks, or migmatites, belong to this simple type. Thus the idea of the origin of pegmatitic magma by a partial re-fusion harmonizes well also with this modern theory of the pegmatites.

The best field illustration of the granite problems may be obtained from a thorough study of the conditions along ancient eroded orogenic zones. Some of those zones, or certain parts of them, have generally little if any granite intrusions, while others abound in intrusive granite masses and migmatites. This difference apparently depends in most instances upon the amount of erosion. In one and the same mountain range it is customary to find the majority of the intrusions in axial culminations, and few if any intrusions in axial depressions. A few examples will be mentioned below, beginning with the Huronian folding zone on the north shore of Lake Huron[2], which the writer knows somewhat from his field-work in 1922. In that summer he

[1] See the brilliant synopsis of recent investigations on the pegmatites by KENNETH LANDES, »Origin and classification of pegmatites». American Mineralogist, vol. 18, 1933.

[2] W. H. COLLINS, »North Shore of Lake Huron». Canada Dep. Mines, Geol. Survey Memoir 143, 1925.

T. T. QUIRKE and W. H. COLLINS, »The disappearance of the Huronian». Canada Dep. Mines, Geol. Survey memoir 160, 1930.

mapped parts of the Serpent River area and the islands near Cutler, as well as parts of the Lake Panache area, where the eastermost point of his excursions was Grey Lake, east of Bell Lake, in that remarkable granite zone where the Huronian »disappears».

The Killarnean granite mass near Cutler is apparently an intrusive mass of the type generally described as batholiths. Eastwards »it fades away in rather interesting fashion across Shedden and Victoria townships, the continuous granite mass giving place by degrees to a multitude of smaller and smaller bands and shreds of granite arranged along the strike of the crystalline shists they penetrate. — — —Apparently the present surface intersects at a low angle the convex eastward pitching roof of the Cutler batholith, thereby throwing some light upon the manner in which such intrusive bodies work their way upwards» (Collins, op. cit. 1925, p. 85). — — — »It (the granite) has developed around itself in these formations a metamorphic zone about half a mile wide but forming longer tips at the ends of the ellipse» (Collins, op. cit. 1925, p. 87). Thus the Cutler granite apparently occupies an axial culmination in the Huronian zone.

Farther away from the Cutler granite, as far as Panache lake in the East, the Huronian sedimentary formations are very little metamorphosed. Quartz veins, in part auriferous, occur. At least some of these are believed to be offshoots from the Killarney granite. The degree of metamorphism becomes appreciable around the eastern part of Panache lake, and small intrusive masses of granite and dikes of pegmatite begin to appear. Finally the Huronian sediments become ultrametamorphic, or even migmatitic, e. g. on the shores of Bell lake.

The »disappearance of the Huronian» takes place fairly rapidly in a continuous belt of granite which trends from Killarney Bay in a northeasterly direction obliquely across the Huronian zone. Eastwards this granite passes over into migmatites, among which Quirke and Collins were able to identify the regular series of Huronian sediments in an ultrametamorphic habit, but almost in their normal sequence, though risen five or six miles higher and eroded as much deeper than the Huronian on the northwest side of the said boundary. The sediments have undergone a metasomatism which has attacked them differently according to their composition, but which in all cases excepting that of the calcareous Espanola formation has finally led to similar end products, i. e. gneisses, and even granites. Especially remarkable is the successive alteration of Lorrain quartzite into porphyry, gneiss, and granite, mainly by introduction of potash and soda. »The whole series of pink gneisses (resulting from the various sediments) indicates an introduction of quartz and orthoclase». The Killarney area, according to Quirke and Collins, exhibits a case of granitization in place, the process being not generally attended by great intrusive movements of magma, although there occurred an introduction of the granitizing »ichors».

In Finland the Karelian schist zone is, in many respects, analogous to the Huronian zone of the North Shore of Lake Huron, a general difference being, however, that the Karelide orogenesis had a more pronounced Alpine overthrust character, the tectonics accordingly being far more complicated, and their sedimentogeneous rocks far more schistous. Large parts of this zone appear to be free from granitic intrusions and only have quartz veins, while other parts are migmatized. The transition between the extreme cases takes place by degrees. Occasional pegmatite dikes mark the first outposts of intrusions. They become more and more numerous and in many areas are soon accompanied by dikes of ordinary granites. At this stage there may occur suddenly either big batholiths of pure granite, or wide areas of migmatites showing potash metasomatism and other phenomena like those in the Killarney area. Quartz veins in feldspar-bearing mica schists are in places very numerous. Such rocks may be spoken of as quartz-veined gneisses, as they in some cases vividly resemble true granite-veined gneisses. Their passing over into the latter within narrow transitional zones is a very remarkable phenomenon, and may be seen e. g. in Karelia, west of Outokumpu mine. In the Karelian of northern Finland intrusions of batholiths and migmatitization of mica schist, quartzites etc. are both well represented, although these migmatites have not yet been studied more closely. Dr. E. Mikkola has lately mapped gneissified or granitized quartzites occurring on a large scale in the districts Muonio and Kittilä in Lapland. In certain northern parts the whole schist zone has been migmatized, as e. g. in southern Lapland, but farther south, in Karelia, only the western »root zone» of the Karelides shows an intense migmatitization, while the eastern margin, which has been thrust over the old foreland, is comparatively free from intrusions.

Very illustrative examples of distorted and intimately mixed quartz-veined gneisses giving place by rapid transition to granite-veined gneisses of almost the same appearance were observed by the writer on the island Olchon and the peninsula Sviatoi Noss in Transbaikalia.[1]

[1] P. Eskola, »On the igneous rocks of Sviatoy Noss in Transbaikalia». Översikt av Finska Vet. Soc. Förhandl. LXIII, 1920—21, p. 8.

In southern Finland the Archaean is largely migmatitic, as probably all geologists interested in granite problems know from the works of Sederholm. Referring to these[1] the writer only wishes to point out certain dominant features of importance to the present discussion.

Intrusive movements of magma in connection with orogenic crustal movements are more conspicuous in southern Finland than they seem to be in the Killarney area. In a recent work[2] on the archipelago east of Helsinki Wegmann and Kranck have presented a fine example of in what degree movements of magma as well as of crystalline masses may be elucidated by tectonical investigations. In many migmatite areas in southern Finland, as shown by the authors quoted, and as is known to the present writer from earlier field experience, the migmatitization has, however, but slightly disturbed the positions that the rocks had attained by crustal movements prior to the invasions of the granitic materials. This fact makes it apparent that the granite magma, either filling narrow joint fissures or forming bigger masses, must have had very little viscosity during its *mise-en-place*.

Sederholm has in his writing greatly emphasized the actively intrusive character of the veins in veined gneisses and therefore designated these migmatites by the special name a r t e r i t e s. Holmquist,[3] on the other hand, has called the veined gneisses v e n i t e s, thereby accentuating his opinion that the veins have originated by segregation from the older rock itself during an ultrametamorphism. To outsiders Sederholm's and Holmquist's discussion, which has lasted more than a score of years, has probably seemed to bear upon the same thing, but actually they have spoken of two different phenomena which both are real and mostly occur together, although perhaps in the Stockholm region, where Holmquist chiefly gained his experience of these rocks, the venite characters are more pronounced, while Sederholm first happened to meet with rather typical injection gneisses. As far as the result of Goranson can be applied here, we see in the venites an illustration of differential anatexis from the closest possible quarters. The veins of the venites being granitic

[1] See especially: J. J. SEDERHOLM, »Om granit och gneis». Bull. Comm. géol. Finl. N:o 23, 1907. — »On migmatites and associated rocks of Southwestern Finland». I, Bull. Comm. géol. Finl. N:o 58, 1923; II, Ibid. N:o 77, 1926.

[2] E. WEGMANN and E. H. KRANCK, »Beiträge zur Kenntnis der Svecofenniden in Finnland», I and II, Bull. Comm. géol. Finl. N:o 89, 1931.

[3] P. J. HOLMQUIST, »Typen und Nomenklatur der Adergesteine». Geol. Fören. i Stockholm Förhandlingar, 1921.

in composition, the solutions from which they have crystallized must be spoken of as magma. Had there been only aqueous solutions under hydrothermal conditions, the segregation should have resulted in quartz-veined gneisses, such as are actually found in many orogenic zones, passing over within narrow limits into ordinary granite-veined gneisses (cf. above).

Grout[1] publishes from the Key Harbor area north of Lake Huron a sketch of »a fold in sediments metamorphosed at great depths. — Where the fold is so sharp that the beds broke, there is a little pegmatite with definitely igneous character». He regards this as an evidence of fusion, although he adds: »(In such rocks) the outcrop rarely shows three dimensions, and it may yet be asked whether the pegmatite might not have been injected from below as an apophysis from some large body at no great distance», and furthermore, in conclusion: »Thus all the examples of fusion in the crust that come to mind prove to be small bodies». In the venites of, say, the vicinity of Helsinki, Grout would find evidences on a regional scale also of this kind, i. e. pegmatitic segregations with no connection with other igneous masses, but this is in itself still no evidence against intrusion in the form of imbibition. Rocks under plutonic conditions and in the vicinity of intrusive masses have been much more permeable than might be imagined. The writer has met with numerous examples of isolated yet intrusive segregations. They are most conclusive when occurring in peridotitic rocks which in themselves are almost potash-free. Single crystals of potash feldspar derived from introduced material (see below) also belong to this group.

The isolated segregations of pegmatite just mentioned are anyhow very characteristic of venites, but these have many other characteristic features by which they may be distinguished from arterites. The venite veins are far more dependent on their main rock in composition, having e. g. crystals of cordierite or almandite where the gneiss portion contains those minerals. The feldspar of the venite may sometimes be acid plagioclase, if the country rock originally was poor in potash. But where potash feldspar is dominant — which is a far more common case — the older rock portion may, none the less, be devoid of potash feldspar, even in rocks which in all probability were not originally poor in potash, such as many leptites. This circumstance, verified by the writer in a number of cases, and subject to further investigation, is a natural consequence of differential anatexis: The

[1] F. F. Grout, »Origin of igneous rocks». Journal of Geology XLI, 1933, p. 217.

potash feldspar has gone into the palingeneous granitic magma and soaked out from the older rock. In an arterite, on the other hand, being a product of injection, the pegmatite usually has thoroughly impregnated the whole older rock with potash feldspar. A widely spread phenomenon, for instance, is the occurrence of phenocryst-like big microclines in the older rock portion that else may have been, say, dioritic. Kranck[1] recently described such microcline grains, referring to them as porphyroblasts, a term which is well applicable, if we only bear in mind that the circulating pore solution in this case probably was a highly liquid pegmatitic magma.

F. F. Grout (op. cit.) discusses the hypothesis of the genesis of magmas by re-fusion formerly advanced for certain granites and the well-known Duluth gabbro mass in Minnesota. He presents weighty arguments against this hypothesis in the form it was given in these cases some thirty years ago, viz. that the intrusive masses originated from earlier sediments and volcanics by a fusion *in situ*. Grout publishes analyses of the intrusives and their supposed sedimentary parent rocks showing considerable divergencies which forbid any assumption of such a mode of origin. I entirely agree with Grout in his argument and any criticism of his paper from my side would not be to the point. Nevertheles, while the argument is conclusive against fusion *in situ*, it apparently does not disprove differential anatexis, be it in the immediate country rock, or in a deeper zone below, or in some more remote place.

Concerning the alternative of derivation from the country-rock it is apparent that, if part of the compounds of a rock were brought into liquid condition and pressed out, the composition of the newly formed »igneous» rock could not by any means be identical with that of the residual rock. Among the examples discussed by Grout the »red rock» around an inclusion of quartzite in gabbro at Pigeon Point in Minnesota (op. cit. pp. 202—203) might perhaps be explained by assuming that the temperature within a contact zone in the quartzite was raised above the melting temperature of the lowest melting quartz-feldspar mixture, which consequently was fused, forming an intergranular liquid in the quartzite from which it could ooze out. To check this hypothesis an analysis should be made of the quartzite, both from near the contact and farther away. The existence of a contact zone impoverished in alkalies and alumina would favour the hypothesis of differential anatexis. As the crystallization temperatu-

[1] E. H. Kranck, »Beiträge zur Kenntnis der Svecofenniden in Finnland III». Bull. Comm. géol. Finl. N:o 101. 1933, pp. 36—37.

res of a gabbro are higher than that of a quartz-alkalifeldspar mixture, such as the red rock in question, a partial re-fusion of an arkosic quartzite would not seem by any means improbable, while a total fusion would hardly take place. The writer has met with examples of dark dikes invading intermediate rocks at whose contacts small aplitic segregations occur, showing an intrusive relation to both the dike and its country rock. Thus it seems to be undoubted that such a process of lateral secretion of differentially fused materials does occur, but of course, never having visited the Pigeon Point locality, the writer would not insist that this explanation be applicable in that particular case.

While it is fairly apparent that big granite masses have not been derived from their immediate country rock, their magma may well have originated by differential anatexis of the down-pressed mountain roots either direct underneath or at the side, depending upon the character of the movement, whether it has been simple down-pressing or overthrust. Juvenile magma oozing from below may have and mostly probably has been added. It may be borne in mind that, from the earth's thermal gradient, the »mushy» zone in which there would exist an intergranular magmatic liquid in the rocks, should be more than 23 kilometres thick (cf. Eskola, op. cit. 1932, p. 468). This magma would be most abundantly squeezed out from those parts of the crust that are moved by orogenesis. Thus there is no great difference between the mode of transport from the birth places of the juvenile and palingenetic magmas. The writer has earlier (op. cit. 1932) discussed some criteria by which to estimate which of these processes has been dominant, and a few fresh points of view will be presented below.

From the thermal gradient the temperature degree, of c:a 700°C, that would be required to keep the last residual pegmatitic magma in a liquid state should be reached at a depth of 23.3 kilometres but, as pointed out above, the gradient would probably be generally raised in the zones of active orogenesis. Thus the exposure of this zone would seem probable. The many features of the deepest Archaean pointed out above form a considerable bulk of accumulative evidence for the belief that erosion in many Archaean areas has exposed horizons that once were in the zone of differential anatexis. The most weighty argument, in the writer's opinion, is the regional occurrence of granitized rocks and migmatites including an enormous amount of apparent venites.

A potash metasomatism, or a chemical process by means of which very different rocks, like quartzites and argillites, become granitic in composition, is found to be a world-wide occurrence in the Archaean. As it is difficult to conceive the transport of potash unter the conditions prevailing in the zone of anatexis in any form of aqueous solution, the writer was led to the conclusion that the agent causing this potash metasomatism, or the granitizing ichor, has been nothing other than granite magma which percolated the mushy rocks or replaced the older rocks where this was possible, or else intruded along the paths of least resistance.

Quirke and Collins, although they do not consider differential anatexis, have expressed an opinion that almost implies such a conclusion, writing (op. cit. p. 98): »In the Panache and Collins Inlet quadrangles erosion seems to have penetrated, about 6 miles, down to where granitic magma was once being made, but apparently it would have to go much deeper to reveal the origin of more basic magma». »The quartz-diabases, the Sudbury norite and related diabase intrusives of northeastern Ontario, exhibit a marked tendency to differentiate towards an aplitic material rich in alkalis and silica. Is it possible that the soda, potash, and smaller amounts of iron and rarer elements required to convert Huronian sediments into granite and gneiss came, by such a process of differentiation, up from a deep-seated zone of diabasic composition, and that some analogy exists between the granite and gneiss of this region and the thin zones of acidic rock which have been developed by differentiation and assimilation at the upper surfaces of diabase sills at Gowganda, Ontario, Pigeon Point, Minnesota, and elsewhere?». This question expresses what the present writer regards as most probable.

Quirke writes in a paper dealing with French River area, which is the eastward continuation of the Killarney region:[1] »The implication of all these things appears to be that here we have a chance to examine the bourne whence plutonic invasions arise», — »The granitic rocks appear to be replacements of sedimentary rocks»— — — »None of the porphyritic masses shows more than obscure indications of having undergone movement as liquid masses — — —». Admitting that some of the batholiths actually exposed might »under favorable tectonic coercion have supplied enough material to coalesce into one or more large batholiths nearer the surface of that time», he concludes: »However, about French River the batholiths were still-born; they died where they came to birth».

While Quirke thus regards the batholiths as »still-born», he and Collins, on the other hand, offer good evidences for a potash meta-

[1] TERENCE QUIRKE, »The structures and batholiths of French River area». The Journal of Geology XXXVII, 1929, pp. 698—99.

somatism, i. e. introduction from below of granitic material, like »new blood into an old body» (Sederholm's expression). Considering the general character of the migmatite formations, in which no features in the early mineral paragenesis point to hydrothermal conditions, this »new blood» or, to use Sederholm's other expression, the »ichors», can hardly be conceived as anything but a highly liquid granitic magma that may very well, in greater or smaller part, have originated by anatexis at deeper levels.

In southern Finland the Hangö and the Helsinki granites contain everywhere biotite-rich schlieric »ghostlike remnants» of older granitic or dioritic rocks. The structure thus indicates an advanced anatexis, but at the same time the sinuous windings of the schliers and the flow structure of the mixture indicate that the mass has been moved as a whole. This must have happened in a liquid magmatic state of a great part though not of the whole of the rock; the intruding magma must have resembled a mush of biotite flakes suspended in the silicate liquid. Excellent photographs of these »nebulitic migmatites with ghostlike remnants» may be found in Sederholm's paper of 1907 (op. cit.), although this very expressive term was not yet used at that time. There are all degrees of gradual transition, from granites with hardly visible remnants to »dictyonitic migmatites», in which networks of flexure planes with introduced potash feldspar mark the channels along which imbibition of granite magma has taken place.

Quirke has in two papers[1] described, from Ontario, various migmatitic rocks of types well known from the migmatite areas of Finland. He applies to these migmatites explanations that entirely disregard the presence of liquid magma. Thus streaked gneisses, many of which could be called veined gneisses, are explained by him as resulting »from inheritance obscured in many cases by distortion of the original structures and by recrystallization of the minerals». The widespread phenomenon that the country-rock of basic dikes has become irruptive anew and brecciated the dike is explained as due to a solid flow, the light rock being supposed to have been more mobile than the dark dike rock. Even breccia-like mixtures of the type usually termed eruptive breccias, or agmatites (Sederholm), are thus interpreted. Sederholm has in his many papers on migmatites laid great stress on such brecciated dikes, seeing in them one of the best evidences for

[1] TERENCE QUIRKE, »Streaks in the deep zone gneisses». Transactions of the Royal Society of Canada, XXV, 1931, pp. 245—257. — »Differential flow in silicate rocks», ibid., 1931, pp. 258—268.

anatexis. The writer must share this opinion, adding, however, that many of the difficulties pointed out by Quirke would disappear assuming that the fusion was only partial. On reading carefully the papers of Quirke and having the theory of differential anatexis in mind, one can not fail to recognize the superiority of the latter theory. Some features of the eruptive breccias may require a special explanation, e. g. the common occurrence of lighter spheres devoid of dark minerals around dark fragments, which is apparently due to a concretionary diffusion towards the fragments.

In conclusion a few words may be said about the force that causes the magma to rise. In the paper on the origin of granitic magmas the connection of the intrusions with orogenesis was strongly emphasized, and many readers seem to have understood that the writer should regard the orogenic coercion as the sole force driving the magma upwards. Professor Hans Cloos wrote a letter on this question, and as his remarks seem to be most important, the writer quotes, with his permission, a few passages from this letter: After having stated his agreement with most of the writer's conclusions Cloos continues:

»Dagegen möchte ich den Begriff Bewegung in diesem Zusammenhang noch etwas genauer präzisieren. Sie setzen Bewegung in diesem Falle sehr nahezu gleich mit Orogenese und Sie sehen die Mitwirkung der Orogenese z. T. in solchen Bewegungsspuren, die ich als granittektonische beschrieben habe. Nun war es allerdings früher meine Meinung, dass die sogenannte Granittektonik grösstenteils den Einfluss einer aktiven Orogenese auf die Schmelze passiv verzeichnet. Aber schon seit 1925 habe ich immermehr hervorgehoben, dass in den Plutonen eine selbständige und aktive Aufwärtsbewegung verzeichnet sei, welche zunächst auch ohne orogenetische Mitwirkung verständlich ist. Es sind also Spuren mechanischer Bewegung nicht ohne weiteres Beweise für orogenetische Mitwirkung. In grossartiger Weise kommt die aktive Vertikalbewegung riesenhafter Plutone in der kalifornischen Sierra Nevada zum Ausdruck — — —. Immerhin schliessen auch solche Befunde die orogenetische Mitwirkung an der tieferen Differentiation keineswegs aus und ich rechne selbst damit».

»Wesentlich anders aber liegen die Verhältnisse in den Südkontinenten. Im Erongo, S. W. Afrika, den ich 1911 und 1919, und im Brandberg, den ich kürzlich im N. Jahrbuch, BB. 66 B monographisch beschrieben habe, haben wir sehr grosse Granitmassen vor uns, die, wenn überhaupt tektonisch, so allerhöchstens durch leichte Senkungen mit oder ohne Brüche präformiert sind. Auch von dem roten Granit der Buschfeldmasse und einer Reihe weiterer Massen, die ersichtlich nur die zufällig zuerst bekannten von sehr viel verbreiteteren Beispielen darstellen, gilt möglicherweise das gleiche. Noch etwas weiteres kommt hinzu. Die von mir untersuchten jungen Granite folgen den über riesige Flächen ausgebreiteten Karrudiabasen auf dem Fuss und hängen mit ihnen auch stofflich zusammen. — — — Diese Diabase sind aber nachweisbar an Spalten über grosse Flächen gefördert und haben geologisch durchaus das Auftreten von Plateaubasalten. Tektonisch teilen die von mir untersuchten Granite den Mangel an Bewegungsspuren, den Sie vom Rapakivi hervorheben. Es scheint mir also, dass der Rapakivi keineswegs die rätselhafte Ausnahmestellung einnimt, wie Sie ihm zuschreiben, sondern dass es anorogenetische Granite in beachtenswerter Menge gibt, und dass ihre Stellung und Entstehung in Ihren Gedankengang noch mit eingeordnet werden müssten».

These remarks seem to be very valuable and the present writer has no objection to make excepting that the reproof directed to him for too much stressing the orogenesis does not seem wholly justified. Actually the writer has also considered an active force besides the orogenic pressure, viz. gravitation, saying e. g. on p. 460 (op. cit.): »— — — the granitic magma being lighter than the surrounding rocks, had a tendency to rise». In this place reference was made to the paper of Wegmann on granite diapirismus.[1] Upward moving masses of granitic magma are by this author compared with salt domes, or diapires. The present writer can see no other force than crustal movements and gravitation that could cause the oozing upwards of those magmatic granite juices whose action is so apparent in the potash metasomatism of the migmatites as well as in the rise of the magma masses of batholithic dimensions. The rapakivi and related intrusives are no doubt most typically anorogenic. The absence of traces of movements in them is nevertheless very puzzling.

To sum up, the writer wishes to present a division of the earth's crust below the zone of weathering into zones showing a different behaviour as far as intrusions and anatexis are concerned.

1) The zones with no truly plutonic granitic or pegmatitic intrusions but with more or less numerous hydrothermal intrusions, chiefly in the form of quartz veins, representing the last residual aqueous solutions derived from crystallizing magmas or dissolved from the surrounding rocks.

2) The zone of intrusions and of injection and potash meta-

[1] C. E. Wegmann, »Ueber Diapirismus». Bull. Comm. géol. Finl. N:o 92, 1930.

somatism. The boundary against the first zone is marked by the first outposts of plutonic intrusions, mainly pegmatitic or aplitic. Going downwards their number increases, and soon there appear big intrusive masses in the loci of least resistance, in form phacolithic, acmolithic, or batholithic. The invaded rocks are increasingly changed in composition by the introduction of granitic material, mainly appearing as a potash metasomatism, and imbibition with potash feldspar. Rocks close to granites in composition may be granitized. The migmatites are mainly arterites with granite veins injected from below. Still little if any partial re-fusion, as this is the zone where temperature was still below, though near, the fusion temperature of the last residual pegmatitic magma.

3) The zone of differential anatexis. In rocks such as argillaceous or arkosic sediments, and in igneous rocks, the most basic ones excepted, there exists an intergranular silicate liquid of granitic or aplitic composition, nearly or wholly saturated with water. Crustal movements and a gravitative control would compel this magma to squeeze out from the rock pores, to collect along fissures and planes of least resistance and to move shorter or longer distances. Through its lesser density as compared with the country-rock the magma would rise, even unaided by crustal movements. The unfused portion of the rock thus becomes impoverished in the granite compounds, and especially the percentage of potash diminishes. On the other hand a rise is noticeable in all the »excesses», like that of silica in quartzite and of alumina in argillaceous rocks. This happens, however, only in rock masses squeezed effectively, and even in them mostly but incompletely. Considerable amounts of the fused materials remain within the rock masses, either in place as an intergranular liquid or collected as pegmatitic segregations in venites. Still further, the removed granitic materials are substituted by granitic magma continually rising from below, partly fed by juvenile sources. This is probably the most common case. Migmatites, partly arteritic and partly venitic, are especially characteristic of this zone. Only very femic rocks like peridotites, metamorphic magnesium-silicate rocks, limestones and, moreover, some quartzites, amphibolites and mica schists rolled in such a way that their interstitial liquids have been squeezed away, have remained free from admixture with granitic veins.

This division into zones is of course quite too schematic wholly to cover the complicated conditions in the earth's crust. In the first place the zones are by no means always strictly horizontal. In orogenic zones the thermal gradients rise. This is chiefly due to intrusion of juvenile magmas more femic than the granite magma. Such basic magmas having higher crystallization temperatures convey much heat from below to the upper spheres. Where the carriage og magma chooses horizontal paths along shear zones and big bodies of basic magma intrude, they may invert the temperature zones altogether in the subjacent strata, so that zones of injection and high temperature mineral facies may occur above those with no intrusions and low temperature facies. An excellent example of this has been presented by Th. Vogt from the Sulitelma region in Norway.[1]

We find rock formations from all the three zones in eroded mountain ranges, especially in the pre-Cambrian. Rock formations that are intensely migmatized or granitised over wide areas and include venitic migmatites with innate granitic segregations are regarded as belonging to the deepest zone, *viz.* that of differential anatexis, it being unthinkable that the temperature in these intimate rock mixtures, whose granitic veins appear to have been segregated in a magmatic state, would not during the process have become exactly the same throughout.

The veins of the migmatites are in the great majority of cases pegmatitic or aplitic; only in the surroundings of intrusive granitic masses may migmatites with truly granitic veins be met with. This is supposed to depend upon the temperature having been above the crystallization temperature of pegmatitic water-saturated magma but below that of ordinary granitic magmas. As yet there is no conclusive evidence of a complete fusion and palingenesis of granites, though it would not seem to be beyond the bounds of possibility. Still less are there any signs of the fusion of more basic rocks. The deepest level exposed by erosion seems to be that of the fusion of aplitic materials.

The author's conception of the granitic magma is that of a silicate liquid, in itself not very viscous, but on its way upwards mostly mushlike from crystals carried along, being either remains of partly refused older rocks or early crystallisations from a juvenile magma. We find the magma permeating the rocks, impregnating them with granite minerals and, as a rule, rising upwards. The author sees in the rise of lighter and lower-melting liquids through heavier crystalline materials one of the chief mechanisms by which the earth's present gravitative stratification has come into existence.

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[1] Th. Vogt, »Sulitelmafeltets geologi og petrografi». Norges Geologiske Undersökelse N:o 121, 1927.

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3.

# ON THE CHROME MINERALS OF OUTOKUMPU.

By

PENTTI ESKOLA.

CONTENTS.



## GENERAL OUTLINE.

The Outokumpu copper-mine in eastern Finland is situated in a geological environment typical of the ancient Karelian mountain zone of East Fennoscandia. A schematic map, a longitudinal section and a cross section (fig. 1) show the mode of occurrence of the ore. The general folding axis of the schist series dips at 10° or 15° in a westerly direction, as indicated by the shading on the longitudinal section.

Wide areas all around the mine are underlain by a coarsely crystalline mica-schist which, farther west, grades over into micaceous gneiss injected by post-Karelian late-kinematic granites. Big masses of the granitic intrusions occur about five kilometres west of the mine, but even at Outokumpu a few pegmatitic dikes derived from this granite have been met with cutting the ore.

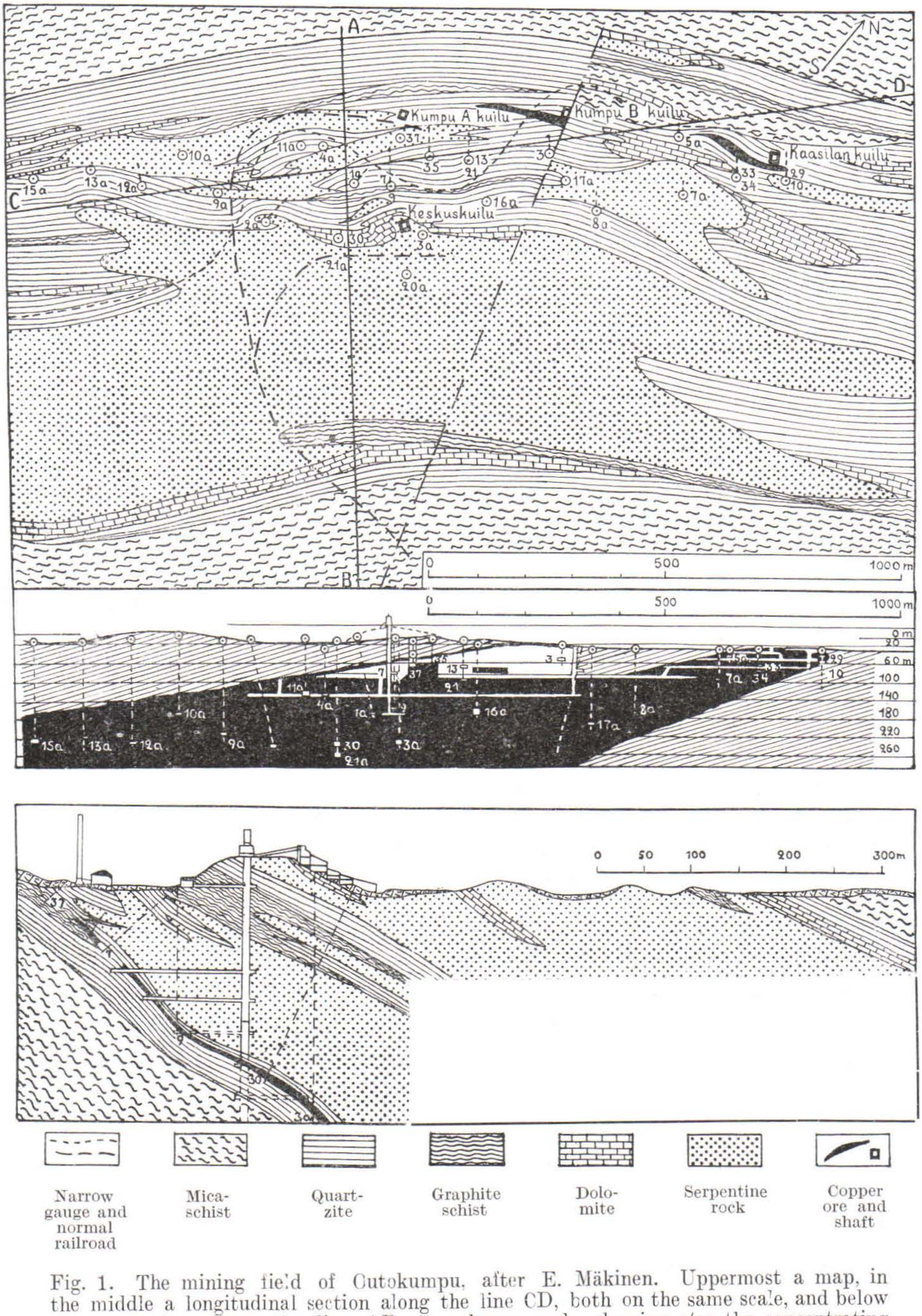


Fig. 1. The mining field of Outokumpu, after E. Mäkinen. Uppermost a map, in the middle a longitudinal section along the line CD, both on the same scale, and below a cross section along the line AB on a larger scale, showing also the concentrating mill and power station. Circles and points on the map and the longitudinal section indicate starting points of diamond drill holes, and dotted lines on all the figures drill holes. On the map the broken line across the area at the shaft Kumpu B kuilu indicates a fault line along which the east side has sunk so that the ore body is met with only at a depth of 100 m. Keskuskuilu = Central Shaft.

The copper ore forms a sheet-like mass, being a brecciated zone in quartzite. The ore has a fairly uniform composition throughout the whole length of the ore body, which is, so far as known at present, about 2.5 kilometres long and from one to 16 metres thick (only in exceptional cases still thicker). Its average mineral composition is:

| | |
|---|---|
| Chalcopyrite .................. | 12 % |
| Pyrite ........................ | 32 » |
| Pyrrhotite .................... | 14 » |
| Sphalerite .................... | 2 » |
| Quartz ........................ | 40 » |
| | 100 % |

At present the Outokumpu mine produces yearly 200 000 (in 1935 to be raised to 300 000) tons of ore which is concentrated in the concentrating mill at Outokumpu.

The ore sheet is overlain by serpentine rock intercalated with quartzite, dolomite, and graphite-bearing schist. The dolomite, in turn, is bordered by skarn rock, mostly diopside and tremolite skarn. These skarn rocks generally show vivid chrome green colours, in many places still more intensified by the presence of chrome garnet, or uvarowite. Patches and streaks, coloured green by some of these minerals, or by chrome mica (fuchsite), may also be seen here and there in the quartzite and even in the mica-schist at the contacts towards the rocks of the serpentine-bearing complex. The chrome minerals are thus fairly conspicuous in the Outokumpu mining field. They were indeed known long before the copper ore was discovered (1910). Thus, the uvarowite of Outokumpu was described by Borgström as early as 1901. As the hill Outokumpu was not at that time the well-known locality it is now, Borgström used, in the title of his paper, the name of the parish, Kuusjärvi, and that of the village, Sysmä, and thus it happened that the Outokumpu uvarowite has become known in the literature as »uvarowite from Kuusjärvi», or »uvarowite from Sysmä» (e. g. by Menzer, 1929).

On the hill Raiviomäki at the W. margin of the area of the map (fig. 1, N. of the drill-hole 15 a), the dolomite is accompanied by anthophyllite-cordierite rock. The dolomite here contains chromite, and the anthophyllite-cordierite rock chrome spinel or picotite, as reported by the present writer as early as 1914 in his Orijärvi monograph (page 245).

The mode of occurrence of chrome minerals at Outokumpu, even on superficial inspection, is likely to suggest the idea that chromium has been rather mobile, and that the chrome minerals have been formed as a result of metasomatic replacement. The discovery, in the summer of 1932, of strange-looking uvarowite-pyrrhotite veins in quartzite at once showed what remarkable ways the transport of chromium really has taken, and at the same time called forth a somewhat comprehensive study of the Outokumpu chrome minerals.

## CHROMITE IN SERPENTINE.

The regular occurrence of the chrome minerals in the close vicinity of serpentine naturally gives rise to the hypothesis that they may have been ultimately derived from this ultrabasic rock. Therefore I determined the percentage of chromium sesquioxide in the serpentine and investigated whether this rock might contain any special chrome minerals, especially chromite, which is supposed to occur as primary crystallizations in dunites.

The serpentine at Outokumpu is fairly variable. Certain varieties consist almost exclusively of dense serpentine of the usual type, showing a relict granularity, supposed to indicate a pseudomorphism after granular olivine. More commonly the serpentine contains much carbonate, probably dolomite, whose mode of occurrence as crystals and aggregates apparently grown into the serpentine in a breccia-like manner makes it probable that it is an introduced material, the carbonate replacing the silicate. Talc is a frequent secondary product. Tremolite in long prisms is commonly present, but in a few cases anthophyllite has been met with instead of tremolite. Remains of unaltered olivine have been observed in many varieties of the serpentine, especially the carbonate-bearing serpentine rock.

Chromium was determined in a sample of tremolite-bearing white-spotted serpentine which was found to contain 0.33 % $Cr_2O_3$, and in another specimen of dark green pure serpentine which gave 0.28 % $Cr_2O_3$.

Minute grains of iron ore are invariably present in the serpentines. In the tremolite- and carbonate-bearing varieties it occurs more richly and in bigger grains, whereas the pure serpentine contains almost solely pigment-like ore. The heavy minerals present were separated by panning from the same specimens in which chromium was determined. The concentrate from the tremolite-serpentine consisted chiefly of iron ore grains, in addition to green amphibole, and proved to contain practically no chromium. Its ore grains were soluble in hydrochloric acid, thus apparently being magnetite. The concentrate from the pure serpentine, again, contained only richly ore-pigmented serpentine and proved to contain 1.60 % $Cr_2O_3$. This result indicates that chromite is present in the ore-pigment which seems to have been separated in connection with the serpentinization. No primary crystallizations of chromite were found in the serpentine. No facts, however, forbid us to assume that all the chromium present in the neighbouring rocks may have been derived from the serpentine rock.

### FUCHSITE, ETC. IN QUARTZITE.

The bands of crystalline quartzite often show frequent green-coloured streaks or seams elongated in the direction of the general folding axis. The green minerals are fuchsite or chrome-mica, chrome-diopside, chrome-tremolite, and uvarowite, or chrome-garnet.

Fuchsite is the most common chrome mineral in the quartzite, occurring either alone or accompanied by brown biotite and iron pyrite. Megascopically the chrome-mica is intensely green and, in thin sections, shows a distinct pleochroism: $\gamma = \beta =$ brownish green $> \alpha$ ($\perp$ the basal cleavage) = bluish chrome green. 2 $V_\alpha$ = about 40°.

An attempt was made to separate the fuchsite by cautiously crushing up fuchsite-rich streaks of quartzite and shaking the cleavage flakes along a sheet of writing paper, whereby the flakes adhered to the paper. The sample thus obtained contained 3.68 % $Cr_2O_3$ but besides, according to a determination of the silica percentage, about 25 % quartz. Thus this fuchsite should contain 4.90 % $Cr_2O_3$, a percentage a little higher than any reported earlier in chrome-micas.

The other chrome minerals in the quartzite occur as streaks or thin layers, or even joint fillings in different directions. The intercalation of quartzite with diopside or tremolite (in this case chromium-bearing) might suggest a primary stratification, as in fact appears to be the case in many parts of the Karelian zone, where dolomite quartzite is often substituted by diopside quartzite. The diopside- or tremolite-bearing layers would in that case originally have been calcareous sand layers. At Outokumpu, however, the rocks are highly sheared up and have no primary bedding or other structural features preserved. Although the quartzite, in all probability, has been originally a sediment, there are no proofs that the lime- and chrome-bearing bands and streaks are of such origin. The irregularly streaky or lenticular shape of the green skarn-like mineral concentrations and their occurrence as fillings of cracks would make it rather more probable that lime-bearing solutions have been introduced to the quartzite from outside sources along the shearing planes. Chromium, in this case, would have been introduced together with lime which may have moved in the form of carbonate.

In many cases the lime- and chrome-bearing silicate minerals in the quartzite have been concentrated richly enough to appear as small masses of skarn — either chrome-tremolite skarn, chrome-diopside skarn, or uvarowite skarn. Especially the latter forms in quartzite only narrow streaks, hardly ever more than one centimetre thick, but most commonly appearing as merely a green film on the schist planes or joints of the quartzite. It is to be noted that where the quartzite contains uvarowite it invariably contains sulphides.

It was in quartzite that the uvarowite described by Borgström was found (cf. below). If the explanation given above is correct, then this mode of occurrence of the chrome garnet would not be essentially different from that in the veins described below.

## CHROME-DIOPSIDE AND CHROME-TREMOLITE FORMING SKARN ASSOCIATED WITH DOLOMITE.

Somewhat bigger masses of diopside and tremolite are associated with dolomite, mostly occurring between the latter and quartzite or serpentine. Here, however, the pyroxene and amphibole minerals are by far not invariably chromium-bearing. Especially the tremolite occurring in serpentine or in dolomite is not coloured green by chromium and shows only the common pale bottle-green tinges characteristic of tremolite-actinolite mixtures rather poor in iron. In such tremolite rock, or tremolite-bearing dolomite, the tremolite frequently forms radial aggregates, and the amphibole may be finely fibrous, asbestus-like.

Diopside skarn, again, is mostly distinctly chrome green, and so is the tremolite associated with the diopside, although the depth of the green tinge is very variable. Such skarn occurs e. g. just N. W. of the Central Shaft on the Outokumpu hill. Here, as well as in other places, the diopside is extremely coarsely crystalline, the prisms often measuring more than 10 cm. The interstices are filled up with coarsely crystalline calcite, in which may be found enclosed well-formed crystals of pyrrhotite tabular parallel to (0001), and grains of pyrite. Frosterus and Wilkman (1916) published the following analyses of the chrome-bearing skarn minerals of Outokumpu (made by E. S. Tomula [1]):

[1] The total iron in the diopside is originally stated as $Fe_2O_3$ 2.80 %. I have recalculated this figure as FeO 2.52 %.

| | Chrome-diopside | Chrome-tremolite |
|---|---|---|
| $SiO_2$ | 52.84 % | 57.74 % |
| FeO | 2.52 » | 2.75 » |
| $Cr_2O_3$ | 0.44 » | 0.64 » |
| $Al_2O_3$ | 1.04 » | 2.35 » |
| CaO | 25.44 » | 14.04 » |
| MgO | 17.26 » | 22.38 » |
| $H_2O$ | 0.88 » | 0.38 » |
| | 100.42 % | 100.28 % |

The question of the mode of origin of these skarn layers is connected with the problem of the dolomite. If this is sedimentogeneous, then it is most natural to assume that the skarn is a usual product of a metasomatic replacement of this carbonate rock, i. e. an ordinary skarn. However, the close connection of the dolomite with the serpentine rock is likely to arouse doubts in this respect. As mentioned above, the serpentine is largely dolomite-bearing in such manner that the carbonate would appear to replace the silicates. In many areas of the same Karelian zone there occurs talc-carbonate rock, or soapstone, in connection with serpentine rock. In the case of soapstone an assumption of a partial replacement of the silicate minerals by the carbonate is hardly dispensible. Could not, then, the process in places have gone a step farther, so as to give rise to a pure dolomite? In the petrology of rocks formed in the mountain zones important scientific conquests are still to be expected through theories unprejudiced by those lines of thought which have led to the opinions which are now prevalent. If the dolomite were a product of a carbon dioxide metasomatism, then the question of the skarn would be still more complicated; perhaps it would have to be regarded as an intermediate product.

An alternative explanation, however, is the one following the ordinary lines of reasoning, i. e. taking the dolomite to be an ordinary sedimentary rock and the skarn to be an ordinary skarn. Were this so, then the partial carbonatization of the serpentine, and the origin of the talc carbonate rocks would be due just to a transfer of the carbonate from adjacent layers to the body of serpentine. In the present state of knowledge this explanation would seem the more probable one. But I am not taking any stand as to this question, which remains for future investigators to solve. I only wish to emphasize that this is one of the cardinal points not only in the geology of the Outokumpu region but also in the great general problem of serpentine rocks associated with carbonate rocks in many ancient mountain chains.

## CHROMITE IN DOLOMITE.

At Raiviomäki, W. of the Outokumpu hill, a prospecting tunnel has been made partly in dolomite, blocks of which have been heaped near the entrance to the tunnel. This dolomite contains prisms of tremolite and crystals of chromite, the biggest of these measuring 1 cm in diametre. The crystals enclosed in pure dolomite have often been preserved in the form of regular octahedra, but in some specimens, especially where enclosed in tremolite or chlorite, the ore mineral occurs in a breccia-like manner, while the amphibole prisms are not so much crushed up. This fact would seem to prove that the chromite had existed before the tremolite was formed.

The ore grains proved to be practically insoluble in acid, even in concentrated nitric acid. A big sample was separated by dissolving the carbonates and silicates in a mixture of hydrofluoric and sulphuric acids, and the presence of large amounts of chromium in addition to iron was ascertained qualitatively.

The chromite is somewhat unevenly distributed in the dolomite, and its percentage is not great, probably less than one or two per cent, even in the richest blocks. As the actual outcrop is no longer accessible, nothing can be said concerning the total quantity of chromite in this occurrence.

The occurrence of chromite in dolomite is strange indeed, and still more remarkable because this is the only mode of occurrence of chromite in a somewhat considerable concentration at Outokumpu. The question of its origin might arouse many kinds of speculations which, in the present state of our knowledge, can hardly lead to any definite conclusion. Again, the course of the reasoning depends upon the explanation adopted for the dolomite. If it could be taken for granted that the dolomite has been formed by a metasomatic replacement of an ultrabasic rock, say serpentine rock, then we could easily understand the chromite crystals as relics from the primary phenocrysts once settled together with olivine. The brecciation before the crystallization of the amphibole would be in accordance with this hypothesis, while it is rendered somewhat improbable by the fact that no such phenocrysts have so far been observed in the serpentine rock at Outokumpu, any more than in neighbouring occurrences of serpentines or related rocks, with the exception of talc magnesite rock (soapstone) at Nunnanlahti, about 80 km northeast of Outokumpu, where minute crystals of chromite may be observed (Frosterus and Wilkman 1916).

PICOTITE AND KÄMMERERITE IN ANTHOPHYLLITE-CORDIERITE ROCK.

In the prospecting channel and tunnel at Raiviomäki there also occurs cordierite-anthophyllite rock accompanied by sulphide ore containing especially pyrrhotite and chalcopyrite. This rock is apparently bordered by the chromite-bearing dolomite described above. Dolomite and tremolite-dolomite rock are in fact exposed at the entrance to the tunnel.

The cordierite-anthophyllite rock is megascopically coarsely crystalline, composed of radial or sheaf-like groups of anthophyllite prisms, up to 5 centimetres long. The interstices of the amphibole prisms are made up by bluish gray greasy-looking xenomorphic cordierite. A rather large quantity of sulphides makes the rock easily decomposable. Chalcopyrite and pyrrhotite are present in approximately equal quantities, while pyrite appears to be less abundant.

Microscopically one finds a surprising number of accessory minerals, such as yellowish brown short crystals of rutile, and minute rhombohedra of ilmenite, xenomorphic irregular grains of staurolite, which in places forms a symplectitic intergrowth with cordierite, occasional rounded grains of red almandite and octahedra of chrome spinel, or picotite. By means of a separation with Clerici's solution I also obtained small amounts of chromite, besides picotite. In rather considerable amount there occurs a reddish brown chlorite mineral, here referred to as kämmererite, being apparently of a later origin than the other minerals.

The picotite is one of the minor constituents, in quantity approximately equalling rutile and ilmenite but considerably less than staurolite. In rather thick slides its colour appears to be cocoa brown, while in thin sections of normal thickness it is yellowish brown, very like staurolite on $\alpha$ and $\beta$. In some of the grains the tinge is greenish. An attempt was made to separate the mineral by means of Clerici's solution, but the small amount obtained was far from pure, the fraction still containing a considerable admixture of rutile, and also of staurolite. Thus the composition, or even the percentage of $Cr_2O_3$, could not be ascertained.

The chlorite mineral here called kämmererite occurs around or near the anthophyllite prisms. It is a chlorite of a pale colour, //c almost colourless, $\perp$ c pale reddish brown, not very unlike the colour of some biotites. The mineral is optically positive with a small axial angle, $\gamma - \alpha = 0.016$. The reddish colour indicates a chrome chlorite, but the percentage of chromium is probably somewhat lower than in other chrome chlorites, either called kämmererite, kotschubeyite, or rhodochrome. A more detailed investigation of this mineral remains to be carried out.

### UVAROWITE AND TAWMAWITE IN COPPER ORE.

As a rule, no chrome minerals can be seen in the ore mass which is a granular or breccia-like mixture of sulphides and quartz. Only one find of uvarowite crystals has come to my knowledge: In 1929 several big crystals of uvarowite were found in the ore brought up from the Central Shaft. A big specimen of it is kept in the mineralogical collection of the University of Helsinki. The ore of this specimen consists chiefly of pyrrhotite with chalcopyrite and somewhat rounded crystals of pyrite showing the forms (100) and (120).

Enclosed in the ore mass are numerous well-formed crystals of dark green uvarowite measuring from 1 to 1.8 cm in diameter and, moreover, a few slender crystals showing the form of epidote. In analogy with the find in the pyrrhotite-uvarowite-tawmawite veins, these crystals are supposed to represent chrome epidote, or tawmawite, but they proved to be perfectly altered into a finely crystalline, nondeterminable mass, and no traces of the mineral in unaltered condition could be detected.

At the side of one of the uvarowite crystals could be detected minute black octahedra of chromite. This chromite appears to be of a secondary origin.

### UVAROWITE-TREMOLITE-TAWMAWITE-PYRRHOTITE VEINS.

At the »Kumpu B» shaft the ore sheet of Outokumpu is cut by a fault with more than 100 metres, perhaps 200 metres, vertical displacement (see the longitudinal section!). In 1930 the main passage along the ore sheet at Kumpu B was united with the Kaasila Mine by a tunnel at the 90 metres level. The rock that was brought up from this passage during the work was heaped up near the entrance of Kumpu B. In this heap, the blocks of which mainly consist of quartzite, I found, in the summer of 1932, several blocks of quartzite traversed by veins in which green uvarowite and bronze brown pyrrhotite formed the most striking constituents. The thickness of the veins was in some blocks only from 1 to 5 cm, but others were much thicker, up to 30 cm or still more. In some of the blocks, the vein could be seen traversing the strike of the quartzite. In other cases, again, the veins are curved and sometimes branching, frequently swelling out into lenticular bodies. This find was, of course, somewhat sensational. So far as I am aware, nothing like these veins has ever been recorded before. The accepted opinion regarding chromium is that only traces of it may be contained in ore veins. Yet here we find *chromium* in considerable amounts, as a true vein element!

The four minerals are all chief constituents of the veins, though pyrrhotite is apparently the most abundant. Besides, the veins also contain considerable amounts of pyrite and chalcopyrite. The sulphides form the cement of a breccia-like mass, in which the uvarowite seems to be idiomorphic wherever it meets the ore mineral. The chrome tremolite is fairly euhedral against the ore, but appears to be much corroded and its crystals are often bent. The tawmawite also has idiomorphic contours against the ore, but unlike tremolite and uvarowite it is largely decomposed.

Uvarowite is the most conspicuous mineral of the vein because of its striking emerald green colour and the comparatively big size of the crystals, up to 0.5 cm in diameter or a little more. When enclosed in the ore the crystalline form with (110) and (112) is well developed.

The specific gravity of the chrome garnet was determined by means of Clerici solution and Westphal balance at 3.75. The mineral was easily separated from the other vein constituents, part of which are much heavier and another part much lighter. A chemical analysis was carried out at my request by Dr. L. Lokka, whom I thank very much for his kind help. The result is quoted under I, while under II is the analysis made and published by Borgström (1901).

| | I | Mol. fig. | | II | Mol. fig. | |
|---|---|---|---|---|---|---|
| $SiO_2$ | 35.88 | 5 950 | | 36.79 | 6 101 | |
| $Al_2O_3$ | 1.13 | 111 | | 1.93 | 189 | |
| $Cr_2O_3$ | 27.04 | 1 779 | 2 044 | 27.54 | 1 812 | 2 027 |
| $Fe_2O_3$ | 2.46 | 154 | | 0.41 | 26 | |
| CaO | 33.31 | 5 939 | | 32.74 | 5 837 | |
| MnO | 0.03 | 4 | 5 953 | — | — | 5 961 |
| MgO | 0.04 | 10 | | 0.50 | 124 | |
| Loss on ignition | 0.18 | — | | — | — | |
| | 100.07 | | | 99.99 | | |

| | I | II |
|---|---|---|
| $SiO_2$: (Al, Cr, Fe)$_2O_3$: (Ca, Mn, Mg) O | 2.91 : 1 : 2.91 | 3.01 : 1 : 2.94 |
| Spec. g. | 3.75 | 3.772 (15°) |
| $n_{green}$ | 1.8467 | 1.8552 |

The index of refraction was determined in a number of prisms by the minimum deviation method and using a Hg-lamp, and the result quoted above is an average of several measurements in the uvarowite from the veins. The mineral from another locality known as Kaasila A (cf. p. 40) gave $n_{green} = 1.8448$. The results proved that the garnet is not exactly homogeneous. Even in one and the same crystal there are apparently zones of different refractive power (and composition), as appears from the fact that the signal images, even in fairly good prisms, were broadened and had blunt outlines.

My colleague, Professor Borgström, kindly let me use his original uvarowite which had been analysed by him. The samples consist of small crystals and crystal groups in the Outokumpu quartzite. The result was $n_{green} = 1.8516$. The value of Borgström, $n = 1.8552$, has been used by Winchell (1927) in the extrapolation of the refractive index for the theoritical end member of his ugrandite series. The present investigation proves the refractive index to be slightly variable and Borgström's result probably somewhat too high. Considering the inhomogeneity of the mineral, the great difficulties in making good prisms of this brittle material and, moreover, the fact that Borgström had no sufficiently intense monochromatic light and made his determination with white light, the difference is by no means surprising.

Anomalous birefringence, different in different concentric zones, is common in the uvarowite.

T a w m a w i t e. Well formed crystals of the epidote form were first observed in the glassy quartzite in a zone measuring one or two cm from the contacts of the veins. After ascertaining that it really was an epidote mineral — which was not quite easily done, as its microscopic characters are not very similar to those of the common epidote or clinozoisite — I soon found the same mineral to be present as one of the chief constituents of the veins themselves, although in a highly altered state. The altered crystals contain large amounts of a finely crystalline dusty-looking birefractive substance whose real character could not be ascertained. As a rule there are, however, uniformly extinguishing individual grains of the epidote mineral left, and in many grains a central part is unaltered, showing the green colour of chrome epidote.

An attempt was made to separate the tawmawite from the quartzitic boundary zone by means of Clerici solution, but the resulting sample was very impure, owing to the alteration products, as even here many of the crystals are highly decomposed. To secure a good sample of the fresh mineral no other way was found practicable than the rather tedious one of picking up from crushed material one after another of the minute crystals, whose average size was perhaps 0.5 × 1 × 2 mm. 0.9 grammes of fairly pure-looking tawmawwite which, however, still contained a few altered grains, was thus picked up, powdered and analyzed by the writer with the following result (I). Under II is quoted the analysis of the original tawmawite from Tawmaw, Burmah, forming with a little chromite a deep green compact rock associated with jadeite rock.

| | I | Mol. fig. | | II | Mol. fig. | |
|---|---|---|---|---|---|---|
| $SiO_2$ | 39.26 | 6 511 | | 37.92 | 6 289 | |
| $Al_2O_3$ | 24.38 | 2 385 | 3 094 | 12.83 | 1 255 | 2 611 |
| $Fe_2O_3$ | 4.18 | 262 | | 9.93 | 622 | |
| $Cr_2O_3$ | 6.79 | 447 | | 11.16 | 734 | |
| CaO | 20.09 | 3 582 | 3 713 | 25.35 | 4 520 | |
| MgO | 0.53 | 131 | | — | — | |
| $H_2O$ | 4.41[1] | 2 448 | | 2.38 | 1 321 | |
| | 99.64 | | | 99.57 | | |

$SiO_2$: (Al, Fe, Cr) $_2O_3$:
(Ca, Mg) 0: $H_2O$ = 6.31 : 3 : 3.60 : 2.37 7.23 : 3 : 5.11 : 1.52

The ratios of the molecular figures of $SiO_2$, $(Al,Fe,Cr)_2O_3$, (Ca,Mg)O, and $H_2O$, calculated from both of these analyses, as shown above, deviate considerably from the epidote ratio 6 : 3 : 4 : 1. In the case of the Outokumpu mineral the too high ratio of silica and water and the too low one of lime are apparently due to an incipient decomposition of part of the crystals, as stated by microscopical examination.

The tawmawite from Burmah shows still greater deviations, probably due to impurities. Besides the differences ascribable to decomposition or impurities, there are apparently other differences: The Outokumpu mineral is comparatively poor in iron and rich in alumina, a »chrome clinozoisite», while the Tawmaw mineral is rather iron-rich, a »chrome pistazite». These differences make themselves noticeable in the optical properties. Although we consequently here have to do with a mixture differing considerably from the original tawmawite, it does not seem advisable to burden the mineralogical terminology with a new name, but instead to use the name tawmawite in a narrower sense for the chrome epidote compound, $H_2Ca_4Cr_6Si_6O_{26}$, and, in a broader sense to designate the isomorphic mixtures of this compound with pistazite, $H_2Ca_4Fe_6Si_6O_{26}$, and clinozoisite, $H_2Ca_4Al_6Si_6O_{26}$.

[1] Loss on ignition.

In the Outokumpu tawmawite the optic axial plane is normal to the plane of symmetry, just as in the Tawmaw mineral, but otherwise than in normal epidote or clinozoisite. The optical character is negative. 2 $V\alpha$ is variable, in places about 50°, but in some grains considerably larger. Variability also appears in the refringence and birefringence. Determination of the indices of refraction gave for $\alpha$ a minimum value 1.695 and for $\gamma$ a maximum value of 1.715, while the birefringence is invariably lower than in quartz, being approximately 0.008 in maximum. Variation in the birefringence appears as a zonal structure, zones of lower and higher birefringence alternating, as best visible in sections // (010). Dispersion of birefringence is hardly noticeable. Pleochroism: $\alpha$ = olive green; $\beta$ = brown; $\gamma$ emerald green. Dispersion of the optic axes distinct $v > \varrho$. Twins //100. Cleavages (001) and (100) distinct. The optical orientation $\gamma$//b, $\alpha \wedge c = 24°$ in the acute angle $\beta$, while in normal clinozoisite-pistazite series the corresponding angle $\alpha \wedge c$ varies from 0° to 12°.

In the tawmawite from Burmah the pleochroism, according to Bleeck, is: $\alpha = \gamma$ = emerald green; $\beta$ = yellow, 2 V = 45°. Bleeck records anomalous deep green and red interference colours, the absence of which in the Outokumpu mineral is probably due to the smaller amount of $Fe_2O_3$.

The apparent easy decomposability of the Outokumpu tawmawite deserves some special attention. This character is the more remarkable as the epidote and clinozoisite minerals are generally exceedingly well presverved and insoluble. Could this be a consequence of the (rather small) differences of the atomic radii of chromium, iron and aluminium? In the spinel-magnetite-chromite group the relations are directly opposite, the chromite (and spinel) being marvellously resistant against all kinds of chemical influences, in nature as well as in laboratory, while magnetite is rather readily decomposable.

Chrome diopside is present in considerable amounts in some parts of the veins, but it is not very conspicuous because of its fine grain and colour, being pale enough to appear colourless in thin sections. It was not more closely studied.

Chrome tremolite as a fibrous mass composed of slender prisms is an abundant constituent of the veins. Its megascopic colour is brownish green. Seen under the microscope as rather coarse cleavage fragments the mineral is disdinctly pleochroic: $\alpha$ pale yellowish green, $\beta$ emerald green, $\gamma$ brownish green. Absorption $\beta > \gamma > \alpha$. The most striking feature in the colours is the brownish (olive) green tinge of $\gamma$ and the pure emerald (chrome) green of $\beta$, a scheme which is diametrically opposite to that in the ordinary, chrome-free, amphiboles.

$\beta // b$, $c \wedge \gamma = 18°$ appr. $\beta = 1.626 \pm 0.002$; $\gamma - \alpha = 0.028$. The optical character is negative and $2\,V\alpha$ large. Specific gravity, determined during separation with Clerici solution and Westphal balance, is 3.00. In the separated mineral 1.61 % $Cr_2O_3$ was determined colorimetrically and, by weighing after a single separation, 52.61 % $SiO_2$. This tremolite is therefore even richer in chromium than the skarn tremolite whose analysis was quoted above, although its megascopic colour is not such pure »chrome green» as that of the skarn tremolite.

The sulphide minerals, pyrrhotite, pyrite, and chalcopyrite, were not studied any further. In a sample treated repeatedly with aqua regia I could detect, by separation with Clerici solution, a small amount of chromite.

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Although this is so far the only find of sulphide veins containing chromium-bearing silicates, mineral masses of this kind are rather widely distributed at Outokumpu. As was said above, the chrome minerals occurring in quartzite frequently form streaky masses or patches which contain sulphides also. This is also the case with the very richest occurrence of uvarowite so far known at Outokumpu, detected during the early prospecting work soon after the discovery of the ore in a small prospecting shaft originally called »Kaasila A» and located southwest of the present Kaasila shaft. Here was found a sulphide-impregnated portion in quartzite. The ore mineral is largely pyrrhotite, besides which there are very well formed crystals of uvarowite showing (110) (112), of the size of peas, and also fibrous chrome tremolite of brownish green colour like that in the veins described above. The form and exact character of this occurrence can no longer be ascertained, but it is hardly to be doubted that it is genetically related to the veins in question.

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It may be emphasized that the composition of the uvarowite-tawmawite-tremolite-sulphide veins is that of skarn. The mode of occurrence, however, is entirely different, and the ordinary conception of skarn as a product of metasomatic replacement of limestone in place could hardly be applied in this case. From my experience in the skarn-bearing regions of southwestern Finland I have but very rarely met with skarn mineral aggregates in the form of veins. One of them is andradite skarn in leptitic gneiss found at Vihiniemi in the parish of Perniö. The vein is a few cm thick, traversing the leptite with curved surfaces greatly like the chrome-bearing veins now described.

## GENERAL CONSIDERATIONS.

De Launay (1893) and many earlier investigators had advocated the theory that the chromite deposits have been formed in connection with alteration processes in peridotites. By his investigation of the chromite deposits of Hestmandö in Norway J. H. L. Vogt (1894) was led to the conclusion that the chromite represents early separated crystallizations in peridotites. This conception has become a canon. It is true that Baumgärtel (1904) showed that chromite may originate by secondary alterations from chrome diopside and other chrome-bearing silicates, just as magnetite has originated as a by-product on the serpentization of olivine. It has been generally believed that such products are quantitatively insignificant, and the dogma of the early separation of chromite and the general immobility of chromium has survived up to the present day.

In one of his latest memoirs Vogt (1926) states that chromium oxide is chiefly »concentrated in the gabbroidic and still more in the peridotitic rocks, only very little, probably at most say about 0.0005 per cent Cr being left for the granitic rocks». The »sole class of chromium deposits, viz. the magmatic segregations of chromite in peridotites, occur exclusively in basic rocks». »The other extreme pole of magmatic segregations, viz. the gold-quartz veins, — — — carry only a trace of nickel, cobalt, and chromium».

Lately, however, Sampson (1929, 1931, 1932), Ross, and Singewald Jr. have partly dethroned this dogma. Sampson found that, »although much chromite may crystallize at a very early stage, a substantial amount of the constituents of the mineral passes into a residual solution and even into a highly aqueous solution capable of considerable migration» (Sampson 1929). Especially Ross (1929) has pointed out the bearing of chromium-bearing silicates, such as chrome-diopside, chrome-tremolite, fuchsite (or »mariposite»), and kämmererite, in this connection, as these minerals, themselves chromium-bearing, are believed to be of a hydrothermal origin, and thus indicate that the chromite associated with them must be of the same origin. In a later paper, Sampson (1931 a) suggests three genetically different classes of chromite occurrences: »First, chromite formed earlier than olivine or contemporaneously with it — — — —. Second: chromite formed at a late magmatic stage and crystallizing with the last truly magmatic silicate, commonly either bronzite or plagioclase. Third: chromite formed from hydrothermal solutions, for the most part immediately preceding or contemporaneous with intense serpentinization».

In the case of Outokumpu all the chromium minerals, including chromite, have apparently originated later than the serpentine rock from which the chromium most probably has been derived. The occurrence of uvarowite and chromite in the sulphidic copper ore clearly indicates that the migration of chromium and the replacement reactions had taken place contemporaneously with the forming of the ore, or a little earlier, but by no means later.

The occurrence of the chrome minerals thus interpreted seems to offer a considerable interest in the discussion of the genesis of the big Outokumpu ore mass. So far two different theories have been advanced as regards their origin. Trüstedt (1921) [1], the discoverer of the ore body, was of the opinion that the sulphide ores were derived from the post-Karelian granite. This hypothesis was consistent with his conception that epigenetic ores generally have been derived from granitic magmas. He pointed to the fact that pegmatite veins probably belonging to this granite are found in the ore, the pegmatite being brecciated and the fragments cemented by typical ore minerals. To Mäkinen (1921), on the other hand, the pegmatite dikes seemed to be younger than the brecciation of the ore mass as a whole, the dikes being bounded by sharp contacts against the ore. Thus the intrusion of pegmatite fixes the upper time limit of the ore genesis, as the pegmatite must have intruded into an already existing ore breccia; the sulphides which have been added to the pegmatite from the adjacent ore show a more coarse-grained texture than the rest of the ore. Instead, Mäkinen, in accordance with J. H. L. Vogt, who had visited Outokumpu, found it more probable that the ore had been brought up by the serpentine rock which forms a large body separated from the ore only by a few metres of quartzite along the whole length of the ore sheet (about 2.5 km). As in the Norwegian intrusive sulphide deposits, the ore would first have been separated as an ore magma, which intruded in a brecciated zone of quartzite.

The conclusion reached by the above investigation, again, fixes the lower time limit of the ore genesis at the migration of chromium and the crystallization of the chrome minerals. Thus the ores can

[1] Trüstedt's views on this question do not seem ever to have been published in any greater detail than in a brief abstract of a discussion after a lecture given by Mäkinen, though he repeatedly advanced them orally on many occations during his life-time (Trüstedt died in 1929).

by no means have formed at the same time as the *mise-en-place* of the serpentine rock occurred. At present we understand, also, that a dunitic rock never can have existed as a magma of the same composition. Lengthy periods of time had probably elapsed after the movements which brought the ultrabasic masses into their present positions, before the extraction of chromium from the serpentine rock and its redeposition in the numerous different minerals took place. Nevertheless, it seems altogether plausible to me that the ore stands in connection with the serpentine rock rather than with the post-Karelian granites, which, with their migmatite-forming and pegmatitic and at last silicic ichors were spread out regionally all over the Karelian areas. No ore masses have been found in apparent immediate connection with such granites. But also with the serpentine rocks the copper ores certainly stay only in a very remote connection. Although the Outokumpu ore, in all probability, has been derived from some magma, it is by no means necessary that the magma should exist at present as a rock and be exposed anywhere.

## SUMMARY.

The writer describes a number of chromium-bearing minerals in different rocks associated with serpentine-rock which is itself very poor in chromium and only seems to contain chromite in the form of pigment-like secondary products. The other chrome-bearing minerals and rocks are: fuchsite in quartzite, which also contains streaks and patches of chrome-diopside and -tremolite, and uvarowite; the latter three minerals, especially diopside, forming skarn deposits associated with dolomite; chromite in dolomite; picotite, kämmererite, and chromite in anthophyllite-cordierite rock; uvarowite and tawmawite with some chromite in quartzeous sulphidic copper ore, and, finally the most remarkable occurrence of veins composed of uvarowite, tawmawite, chrome-tremolite with sulphides, mostly pyrrhotite, and also containing chrome-diopside and chromite.

The chromite, as well as all the other chromium-bearing minerals of this locality, is in all probability of a hydrothermal origin. The occurrence of chromium at Outokumpu illustrates the ability of this element to migrate and to take part in metasomatic replacements.

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4.

# THE TERM »METAMORPHIC DIFFERENTIATION» FIRST PROPOSED BY F. L. STILLWELL.

By

PENTTI ESKOLA.

In a recent paper entitled »On the metamorphic differentiation of rocks» (Comptes rendus de la Société géologique de Finlande N:o 5, Bull. Comm. géol. Finl. N:o 97, 1932) I made a trial to classify the metamorphic phenomena involving changes of composition for which the term »metamorphic differentiation» was used. Unfortunately I was unaware of the fact that this term had been used earlier by F. L. Stillwell who directed my attention to his works »The Metamorphic Rocks of Adélie Land» (Scientific Reports of the Australasian Expedition 1911—14, Series A, Vol. III, Part I) and »The Rocks in the immediate neighbourhood of the Broken Hill Lode and their bearing on its origin» (Memoir Geological Survey, New South Wales, N:o 8, 1922, App. II, pp. 354—396).

Stillwell's treatise of the metamorphic rocks of Adélie Land has not been available to me in original. From abstracts of its contents and from the memoir on the rocks near the Broken Hill Lode (pp. 23—25) most if not all of the phenomena described by Stillwell appear to be related to those dealt with in my paper. The »pegmatitic gneiss» thus explained from the Broken Hill Lode district, contained as thin veins in darker gneisses, would, however, rather seem to be identical with the veins of venitic migmatites (cf. my paper on »Differential anatexis» in this volume). Epidosite rocks found »in small masses of elliptical section, with the longer axis usually parallel to the schistosity, but sometimes to the bedding plane» might perhaps be identical with elliptical nodules explained as calcareous concretions of premetamorphic origin, but it is also possible that they as well as the other various rocks described by Stillwell have differentiated during the metamorphism according to the concretion principle.

The purpose of the present note is simply to correct my omission in the earlier paper, and to call attention to the important and interesting works of Stillwell.

5.

# EINE BEMERKUNG ZUR MINERALFAZIES DES ARCHÄICUMS

von

Pentti Eskola.

Sehr oft begegnet man in der Literatur der Behauptung, die Gesteine des archäischen Grundgebirges gehören ganz allgemein zu derjenigen Mineralfazies, welche auf die höchsten Bildungstemperaturen und -Drucke hinweist. Charakteristisch ist z. B. die Aussage von L. Kober in seinem neulich erschienenen ausgezeichneten Buch:[1] »So entsteht die so eigenartige Katafazies der Gesteine der alten Massen, in der Aufschmelzung, Durchschmelzung, Intrusion und Tektonik aufs innigste sich verbinden».

Diese Behauptung hat offenbar ihren Grund einerseits in der Auffassung, dass das Grundgebirge am tiefsten denudiert worden sei und dass daher die jetzt aufgeschlossenen Teile desselben sich zur Zeit ihrer Bildung in sehr tiefen Zonen der Erdkruste befunden hätten, anderseits in der Tiefenzonengliederung von Grubenmann, der die sogen. katarchäischen Gneise Finnlands zu seiner Katazone rechnete.

Nun sind die metamorphischen archäischen Gesteine aber keine Katagesteine. Nach der Fazieseinteilung finden sie ihren Platz meistens in der Amphibolitfazies, die der Mesozone Grubenmanns entspricht. Grubenmann selbst hat die für das archäische Grundgebirge so überaus charakteristischen Amphibolite in die Mesozone geführt. Er betont auch die Tatsache, dass im Archäicum keine Eklogite vorkommen, die nur in der Katazone zu Hause sind. Die Amphibolite sind ganz besonders in den »katarchäischen» Gneisgebieten verbreitet. Sie bilden Einschlüsse in den Gneisen und wechseln mit denselben derart, dass es ganz unmöglich ist für die letzteren eine grössere Bildungstiefe anzunehmen als für die Amphibolite. Wenn die Bildungsbedingungen für diese beiden Gesteine

[1] L. Kober, »Das Weltbild der Erdgeschichte». Jena 1932, S. 13.

verschieden gewesen sind, so kann nur eine höhere Temperatur und grössere Tiefe für den Amphibolit in Frage kommen; es sind nämlich die Gneise grossenteils primäre Eruptivgneise, sie haben ganz sicher etwas später und niedriger kristallisiert als die Amphibolite. Auch die Granulite, deren Mineralzusammensetzung möglicherweise auf eine grosse Bildungstiefe hinweisen könnte (was doch gar nicht wahrscheinlich ist) und die von Grubenmann in die Katazone geführt wurden, sind im Archäicum viel weniger verbreitet als in den jüngeren orogenen Zonen.

Wo im archäischen Grundgebirge Abweichungen von der vorherrschenden Amphibolitfazies vorkommen, sind sie in den meisten Fällen Mineralfazies, die zu noch niedrigeren Bildungstemperaturen gehören als die Amphibolite. Die Epidotamphibolitfazies hat in manchen Gebieten eine regionale Verbreitung.[1] In Zentralfinnland sind helsinkitische (unakitische) Gesteine regional verbreitet.[2] Auch in den obengenannten »katarchäischen» Gneisen, z. B. den Granitgneisen Ostfinnlands, ist Epidotbildung recht häufig und reichlich.

Wo gelegentlich im Archäicum Gesteine vorkommen, die einer höher temperierten Mineralfazies angehören, sind sie immer Intrusivkörper, die ihre primäre Fazies reliktisch erhalten haben.

Es leuchtet ein, dass die für die archäischen Gesteine charakteristische, jedenfalls in ziemlich grossen Tiefen entstandene Mineralzusammensetzung der Mesozone, oft sogar der Epizone Grubenmanns entspricht. Die Hauptwirkung des grossen Druckes ist offenbar nur die Zurückhaltung der Mineralisatoren und somit eine Erniedrigung der Kristallisationstemperatur gewesen.

Wenn man doch die archäischen Gesteine in die Katazone einführen will, so bedeutet das nur, dass man damit annimmt sie seien in sehr grossen Tiefen entstanden, während sie nach der mineralogischen Zusammensetzung und der Vergesellschaftung als Mesogesteine gelten sollten. Hierin kann man einen Widerspruch in der Tiefenzonengliederung überhaupt erblicken. Grubenmann selbst wollte doch ausdrücklich, dass die Zugehörigkeit zu einer Tiefenzone nur nach der Mineralzusammensetzung und nicht nach irgend welchen Annahmen hinsichtlich der Bildungsbedingungen entschieden werden sollte (siehe »Die Kristallinen Schiefer», 2 Aufl. 1910, S. 139). Besser wäre denn die mineralogisch verschiedenen Gesteinsgruppen nicht Tiefenzonen, sondern z. B. Mineralfazies zu nennen; dadurch würden wahrscheinlich derartige Irrtümer wie der hier angedeuteten vermieden.

[1] Siehe z. B. Tom Barth, »Kalk- und Skarngesteine im Urgebirge bei Kristiansand». Neues Jahrb. f. Mineralogie etc. B.B. LVII, Abt. A, 1928 S. 1060—1108.

[2] W. W. Wilkman, »Ueber Unakite in Mittel-Finnland». Fennia N:o 15, 1028.

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