On the formation of a carbonate-bearing ultrabasic rock at Kviteberg, Lyngen, northern Norway.

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With 5 text figures and 1 map.

Abstract.

An area of crystalline dolomite, schists, and gneiss including an ultrabasic body at 60° 35′ N and 20° 18′ E is described petrographically and structurally. The ultrabasic rock contains enstatite, olivine, and dolomite as essential minerals. Overfolding and thrusting due to pressure from NW, part of the Caledonian orogeny, are described.

Two modes of formation of the ultrabasic: 1, injection of an utrabasic magma which crystallized in place; and 2, by metamorphic differentiation, are discussed theoretically and then evaluated in the light of the field relationships and structural and petrographical observations. Because the theory of formation by metamorphic differentiation accords with all of the observations while the magmatic mode of origin does not, the conclusion is drawn that the ultrabasic rock at Kviteberg is a metamorphic differentiate.

Introduction.

The area which is desribed in this paper is located in North Norway on the east side of Lyngen peninsula, near the town of Lyngseidet, at 69° 35′ N and 20° 18′ E. The Lyngen gabbro occupies the major portion of the Lyngen peninsula, with a fringe of metamorphosed sediments occurring most of the way along both sides of the peninsula. Near the gabbro the dips are generally towards the WNW (Pettersen, 1891) and become quite flat to the E of the gabbro across Lyngsfjord (Padget, 1955). In the metamorphosed sediments about

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5 km E og the Lyngen gabbro there occur ultrabasic bodies at Sandviken and Kviteberg (Pettersen, 1891). The ultrabasic body at Kviteberg and the immediately surrounding rocks have been the object of the present study.

Petrography.

Ultrabasic. The ultrabasic body at Kviteberg consits of enstatite and olivine with amphibole (rather Mg-rich actinolite), spinel, magnetite, pyrite, and in one case diopside as accessory minerals, and serpentine, anthophyllite, phlogopite, talc, and calcite as secondary minerals. Dolomite is usually present and should probably be considerer as an essential mineral.

The micro-texture is medium- to coarse-grained hypautomorphic.

If dolomite is not considered to be an essential mineral and if the ultrabasic rock is assumed to be magmatic, the rock fits well into Johannsen's classification (Johannsen, 1938, p. 435), receiving the symbol 418 and therefore being a saxonite. The mode of origin will be discussed in detail later (p. 118—124).

Thin-section study of a number of samples from the ultrabasic has revealed the following characteristics:

An orthorhombic pyroxene is always quite abundant in rather coarse grains. The optical data and x-ray powder patterns indicate that the Fe content varies, but never exceeds that of bronzite. Enstatite ($n_\gamma < 1.678$) is more common, however, than bronzite. Olivine is usually present in fairly large, much serpentinized grains. It is optically positive with a very large 2 V. Actinolite (rather Mg-rich) is generally present, usually in small acicular grains and in small quantity. It appears to be a secondary mineral replacing pyroxene. Dolomite is usually present in rather large grains, often intergrown with pyroxene. Calcite is also usually present in small, irregular, interstitial grains and in cleavage cracks in other minerals. Both magnetite and pyrite regularly occur as accessory minerals in, generally, quite small amounts. Phlogopite is often present in small infrequent grains. Deep green spinel is an important constituent in one sample. Diposide is a major constituent in only one section, then being intimately intergrown with dolomite; clinopyroxenes are otherwise completely absent. Rare constituents which have been identified in some sections are anthophyllite, chlinochlore, muscovite, talc, and hematite.

Metamorphosed sediments. The surrounding metamorphosed sediments are, from Rottenvik eastwards to the ultrabasic body:

1. A very garnet rich biotite-hornblende sichist with quartz and plagioclase (acidic andesine). Apatite is moderately abundant; zircon is very rare except as tiny grains in biotite surrounded by pleochroic halos; magnetite is rare; calcite is common in very small, interstitial grains with apophyses into the cleavage cracks of biotite and hornblende. Quartz shows undulatory extinction and the plagioclase sometimes has bent twin lamellae.

2. Dolomite. A moderately coarse-grained, crystalline dolomite with interstitial calcite and scattered crystals, veins, and clusters of white diopside. (As the diopside is transluscent in pieces up to ca. 2 mm thick it may perhaps be called malacolite.) The diopside has been observed to occur in single crystals up to 40 cm × 20 cm in size. In some places the diopside constitues the major portion of the rock, dolomite being present only as a subordinate groundmass, but for the most part it occurs as isolated crystals in the dolomite (fig. 1).

3. A banded series of schists and dolomite layers, the former predominating. The schists are garnet rich biotite-hornblende schists

Fig. 1. The dolomite at Kviteberg. Below the hammer can be seen the dolomite (dark grey) with numerous diopside crystals. Above the hammer the diopside (light gray) is more abundant than the dolomite which occurs as lenses. (Photo, P. H. Reitan.)

Dolomitten ved Kviteberg. Under hammeren ses dolomitten (mørk grå) med diopsidkrystaller. Over hammeren dominerer diopsiden (lys grå) med dolomit bare som linser. (Foto, P. H. Reitan.)

with rare conglomeratic layers. Thin-section study shows the schists to have been subject to intense post-crystalline shearing. The garnets are rich in inclusions. Kyanite is locally an important constituent and shows undulatory extinction. Quartz, showing undulatory extinction, and plagioclase are moderately abundant. Skarn development is frequent. This series continues to the ultrabasic body, dolomite being immediately adjacent to the ultrabasic. The transition to the ultrabasic is gradual, hypersthene crystals first appearing in the dolomite, and then, together with olivine, increasing in density until the basic minerals dominate.

Eastwards from the ultrabasic occur the following:

4. The eastern contact between the ultrabasic and the surrounding rocks is also gradational. Over a distance of about two meters there is a gradual transition from a hypersthene rich rock with

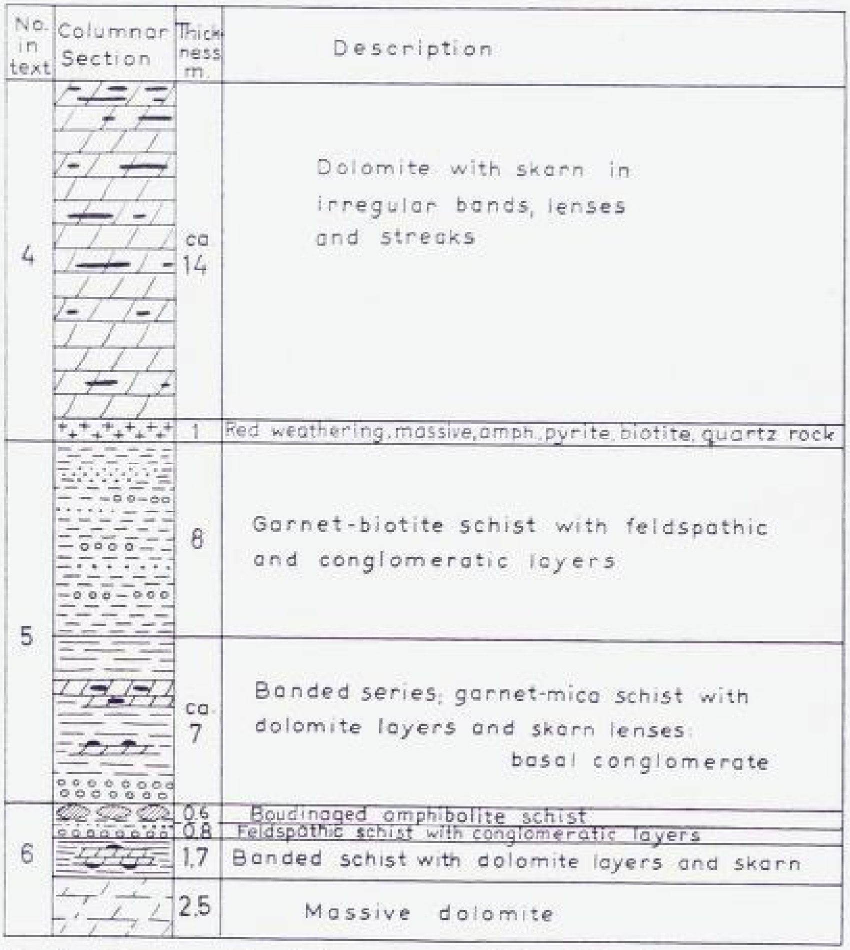

Fig. 2. Columnar section of the rocks nearest the ultrabasic on the east side.

Skjematisk fremstilling av lagrekkene nærmest ultrabasitten på østsiden

only a very small percentage of carbonates to a skarn rich dolomite. The dolomite E of the ultrabasic is about 12 m to 14 m thick and contains skarn in lenses, bands, and irregular streaks. At the base of this unit there is a red weathering, massive, pyrite rich amphibole-quartz-biotite rock.

5. A fissile garnet bearing biotite-quartz schist with porphyroblastic "augen" of plagioclase and K-feldspar. This unit is about fifteen meters thick with carbonate layers and adjacent, boundinaged

Fig. 3. Overfolded schist layer in the dolomite. (Photo, P. H. Reitan.)

Overfoldet skiferlag i dolomitten. (Foto, P. H. Reitan.)

skarn layers occurring near the bottom. There is a basal quartz and feldspar pebble conglomerate. Quartz occurs in "trains", veinlets, and stringers; the biotite is strongly pleochroic and very well oriented, being best preserved in the stress shadows of the feldspar "augen"; the garnets are very rich in inclusions; the plagioclase (basic oligoclase) is strained, sometimes somewhat rounded, and surrounded by envelopes of small quartz and K-feldspar grains; K-feldspar occurs as clear "augen" showing very weakly developed polysynthetic "cross-hatch" twinning and with myrmekitic boundaries, and as small grains in stress shadows together with quartz; apatite and zoisite are rare. The examination of the rock in thin-section reveals it to be a considerably sheared and somewhat recrystallized rock.

6. A banded series containing boundinaged amphibolite schist, feldspathic schist with thin conglomeratic layers, banded schists and dolomite layers with diopside rich, boudinaged skarn bands, and massive dolomite at the base. This unit is about five and one half meters thick.

Fig. 4 a. Overfolds and thrust in the schists north of Kviteberg.
(Foto, J. J. C. Geul.)

Overfoldninger og skyvning i skiferen nord for Kviteberg.
(Foto, J. J. C. Geul)

7. Varied garnet rich amphibole-quartz-plagioclase schists, sometimes containing thin limestone bands and sometimes containing veins rich in quartz and plagioclase.

8. Gneissic rocks containing microline, biotite with zircon in pleochroic halos, quartz, garnet, muscovite, plagioclase, apatite, and opaque minerals. The gneissic structure is marked by "trains" of quartz grains and moderately well oriented biotite and muscovite. The grain size is highly variable, the microline crystals being the largest, often surrounded by biotite and small quartz grains. The amount of microline increases eastwards.

Structure.

The dip of the schists, gneiss, and dolomite is consistantly to the west; the strike in the area varies from N 20 W to N 10 E. In the western part of the area the dip is about 40^g and in the eastern part it is about 25^g. At two places overfolding has been observed.

b. Detail of fig. 4 a. (Photo, J. J. C. Geul.)

Detalj av fig. 4 a. (Foto, J. J. C. Geul.)

In the dolomite along the coast between Rottenvik and Kviteberg a thin layer of biotite schist was seen. By following this layer it can be seen that it is overfolded towards the ESE, the axes of the folds striking N 20 E and plunging 20ᵍ S (see fig. 3). The dolomite, which has apparently undergone considerable post-tectonic recrystallization, shows consistant dip to the west with no traces preserved of the overfolding revealed by the included layer of schist.

The other locality at which overfolding has been observed is in a vertical outcrop north of Kviteberg. Here, in a veined garnet bearing, amphibole-quartz-plagioclase schist, overfolds towards the ESE can be seen which have fold axes striking N 15 E and plunging 20ᵍ S; the axial plane dips 20ᵍ NW. In this outcrop there can also be seen a thust plane which strikes N 5 W and dips 15ᵍ W (fig. 4, a & b).

These observations indicate pressure from the NW which caused overfolding and thrusting within this area, undoubtedly in connection with the Caledonian orogeny.

The contacts of the ultrabasic are conformable to the surrounding rocks (fig. 5) though it is itself quite massive.

Fig. 5. The schists (banded) on the east side of the ultrabasic rock (medium grey). (Photo, J. J. C. Geul.)

Skifrene (båndete) på østsiden av ultrabasitten. (Foto, J. J. Geul.)

Genesis of the ultrabasic rock.

Two possible modes of formation of the ultrabasic rock at Kviteberg must be considered. They are: 1, injection of an ultrabasic magma which crystallized in place; and 2, formation by a process of metamorphic differentiation.

The ultrabasic rock may be supposed to have crystallized from a magma which was intruded into the dolomite and which was very rich in magnesium and relatively poor in silicon and the alkalis. The dolomite can be seen on each side of the ultrabasic rock. The transitional boundaries would then be presumed to be due to reaction between the magma and the dolomite and pneumatolytic alteration of the dolomite. This mode of formation has been ably discussed and advocated for another carbonate-bearing ultrabasic rock called Sagvandite (Barth, 1926, 1930), which occurs about 60 km southwest of Kviteberg. We do not feel that we can improve on nor add to Barth's presentation of the theory, although certain differences between the Kviteberg ultrabasic rock and Sagvandite should be pointed out. Sagvandite contains bronzite and magnesite as essential minerals with the latter constituting 9.2 % of the rock (Barth, 1926, 1930). The Kviteberg ultrabasic contains enstatite, olivine, and dolomite as essential minerals, the latter being of variable concentration but never exceeding about 2—3 %.

The theory of formation by metamorphic differentiation is based on the principle that the relative stability of minerals is dependent on the compositional and P—T-environment in which they find themselves. Specifically, minerals of high mol volume are relatively unstable in zones of high pressure while minerals of low mol volume are relatively more stable. Even though minerals, both of high and low volume, may be relatively unstable in zones of high pressure with respect to the same minerals in zones of low pressure, the relative difference in stability is greater for minerals of high mol volume. In zones of high pressure the relative stability of minerals of low mol volume, those which more efficiently concentrate cations (and anions), will be less reduced than that of minerals of high mol volume. Conversely, in zones of low pressure the relative stability of minerals of high mol volume, those which effectively utilize available space, will be more increased than that of minerals of low mol volume. This is nothing more than the application of the principle of Le Châtelier to a specific case. It also follows directly from the equations of thermodynamics which state the relationship between free energy, mol volume, and pressure (see e. g. Barth, 1952, pp. 317, 318, and Ramberg, 1952, pp. 215—220).

Temperature and original composition will also play a role in determining the relative stability of the minerals involved and will thereby influence the exact mineralogy and chemistry of the rocks which are formed. Another factor which will be of some importance to the composition of the final product is the diffusion rate of the elements or ions involved, as those elements which are not required by the minerals preferred in the high pressure zone must tend to diffuse away.

This process leads to a residual concentration of those elements which go to make up the minerals of low mol volume (olivine, pyroxene, amphibole etc.), i. e. Mg, Fe, and partly Ca, thus resulting in the formation of basic or ultrabasic rocks.

As neither theory can in general be eliminated on theoretical grounds, both must be entertained and evaluated for each specific case in the light of the observations which have been made.

For the ultrabasic body at Kviteberg the general geological setting is not incompatible with either explanation. The large Lyngen gabbro, on which no published results of intentive study are available, which may be magmatic, lies close by. If then, the Lyngen gabbro and the ultrabasic rock at Kviteberg are magmatic, the magma which crystallized as the ultrabasic may have been an ultrabasic differentiate from the Lyngen gabbro magma. But if the ultrabasic rock is metamorphic, the general structural setting allows for the possibility of local, intense pressure differences. The area is in the Caledonian rocks in which thrusting, gliding, and overfolding are well known, and very near by (see p. 117) thrusting and overfolding have been observed in the schists and dolomite. Thin-section examination of these rocks has also revealed that they have been subject to intense shearing. The Lyngen gabbro, which is at least in part layered, has also been subject to quite intense deformation including overfolding and thrusting and, as seen by thin-section examination, quite intensive shearing.

Both explanations are faced with the difficulty of accounting for the intimate association between the Ca-rich carbonate (dolomite, which does not appear to be secondary, within the ultrabasic, in the transitional zone, and adjacent to the ultrabasic) and the Mg-rich, Ca-poor minerals of the ultrabasic, especially the occurrence of enstatite instead of a Ca-bearing pyroxene. Both must then assume that the P—T-conditions were such that the Ca-bearing pyroxenes were unstable at the time when the ultrabasic was formed. This assumption, however, strains the magmatic explanation, as Ca-bearing pyroxenes are extremely common in magmatic rocks formed from magmas sufficiently rich in Ca. It is quite difficult to imagine what sort of P—T-conditions, which could be conveived of as having existed within the crystallizing magma which was reacting with and assimilating dolomite, could make Ca-bearing pyroxene unstable. One might propose that the magma was intruded into the dolomite, pushing it aside, and that therefore reaction with the dolomite was confined to the transitional boundary zones. Against this proposal is the lack of the necessary deformation structures in the dolomite and schists near the ultrabasic body, and the presence of dolomite, albeit in small quantities, throughout the ultrabasic rock. However, an area of, e. g., intense pressure and shear is not the sort or area in which one could expect a magma to remain. Nor is the location of the assumed intrusion the most likely. Dolomite is a notoriously incompetent and plastic rock during metamorphism. It seems unlikely, therefore, that a crack would form in the dolomite into which intrusion would take place, but rather just the opposite — that the dolomite layers would be the most "well sealed" in the area.

The explanation by metamorphic differentiation finds the lack of Ca-bearing pyroxenes difficult too. However, it must be remembered that the proposal of a zone of high pressure necessitates the proposal of a zone or zones of relatively lower pressure elsewhere in the area. Therefore there must be zones of low pressure into which the material from easily decomposed minerals in the zone of high pressure migrates. As carbonates are extremely fugitive under metamorphism it would be natural to assume that the Ca would be in great demand for the formation of calcite in low pressure zones where CO_2 was being relatively enriched, such that only the Mg from the decomposing dolomite would be available for the formation of the minerals of low mol volume which were to remain as the residue in the high pressure zone. That is, the free energy of Ca in calcite in low pressure zones would have been so much lower than the free energy of Ca in a possible pyroxene in the zone of high pressure that Ca would have migrated out of the zone of high pressure into surrounding low pressure zones, while the Mg remained behind, being required to form minerals of low mol volume in the zone of high pressure. The dolomite crystals which are found in the ultrabasic would then represent the last relics of the original dolomite, those which had not yet completely decomposed when the process stopped. The location of the ultrabasic is quite in accord with the metamorphic mode of origin. Zones of, e. g., intense pressure and shear would be expected to occur in weak, incompetent rocks, or even more in areas where such rocks alternated with more competent rocks, where thrusts would most likely be localized.

Both explanations can offer satisfactory explanations for the transitional boundary relations between the ultrabasic rock and the surrounding dolomite. In both cases material released from the present site of the ultrabasic, whether these are magmatic "emanations" or the disperse phase resulting from the decomposition of unstable minerals, could result in the formation of a transitional boundary, skarn in the adjacent dolomite, and the addition of the necessary constituents to form the crystals and concentrations of diopside in the nearby dolomite.

One might object to the metamorphic theory in connection with the source of the Si which is present in the ultrabasic rock. If the ultrabasic is surrounded by dolomite, how did all the Si get to the site of the ultrabasic if constituents would only migrate from the zone of high pressure? In answer to this objection it must be pointed out that no pure dolomite has been observed in the area. In most cases rather thin dolomite bands alternate with schists predominating in silicate minerals including such relatively Si-rich minerals as quartz, micas, and feldspars. The ultrabasic was most probably not formed in a pure dolomite layer, but rather in a zone rich in dolomite but with considerable quantities of interlayered schists. Thus the Si content of the ultrabasic was an original constituent of the zone in which the ultrabasic was formed.

Another problem which must be explained is the abundance of secondary calcite and its presence in all of the various rocks in the Kviteberg area. On can, of course, propose that the area has been "soaked" by late hydrothermal solutions rich in dissolved calcite. Such solutions could not have been derived from a magma which gave rise to the ultrabasic rock, for such a magma would necessarily have been extremely rich in Mg and utterly poor in Ca (to have resulted in a Ca-poor pyroxene after having assimilated appreciable quantities of dolomite). Nor, for the same reasons, could these solutions have been derived from a magma which gave rise to the Lyngen gabbro. This prosess would, then, necessarily have been quite independent of all other events in the geological history of the area, and the solutions could only be attributed to some unknown source. We prefer, however, to attempt to arrive at an explanatory sequence of events which are interrelated, insofar as this is possible, and in which the proposed events follow naturally from those preceding. We would therefore prefer to relate the anbudance of secondary calcite to the formation of the ultrabasic rock.

If the ultrabasic rock is believed to be magmatic this relationship is difficult to find. If the injected magma was so rich in Mg and so poor in Ca that even efter reaction with and assimilation of dolomite the pyroxene which crystallized was enstatite, then there can have been no excess of Ca to be contributed to the surrounding rocks to form calcite. If the magma was injected into the dolomite and reaction was confined to the border zones, the same difficulties prevail. The stable pyroxene was enstatite, therefore there can have been no appreciable content of Ca in a magma from which the ultrabasic crystallized.

If, on the other hand, the ultrabasic rock is a metamorphic differentiate, the Ca was derived from the zone of high pressure in which the ultrabasic formed. As mentioned previously (p. 122), the Mg of the dolomite would have remained behind in the zone of high pressure, being required for the formation of the minerals of low mol volume which were most stable in that zone. The Ca escaped with or was demanded by the escaping CO_2 and formed calcite as a secondary mineral throughout the surrounding area.

Because a magmatic mode of origin is only sometimes in accord with the observations we have made in the area, while the mode of formation by metamorphic differentiation is always in accord with our observations, we prefer to believe that the latter must have been the process by which the ultrabasic rock at Kviteberg was formed.

Geologic history.

The geologic history of the Kviteberg area can be summarized as follows. First there was a period of metamorphism during which crystalline schists and gneisses and crystalline dolomite formed. Second there was a period of deformation, which was locally quite intense, during which the ultrabasic rock was formed in a zone of extreme pressure. This was followed by a period of rather quiet compression during which skarn layers and the ultrabasic body were boundinaged and some post-tectonic recrystallization took place, including the distribution of calcite such that it, throughout the whole area, can be seen as tiny, intergranual grains and in cleavage cracks in other minerals.

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several other students of ultrabasic rocks even though the occasion to cite them in any specific connection in the text has not arisen. They are: Bennington (1956), Sørensen (1953, 1955), and Tuominen and T. Mikkola (1950). The ideas presented in these papers have contributed to the development of our ideas on the formation of the ultrabasic at Kviteberg.

Norsk sammendrag.

Om dannelsen av en karbonatførende ultrabasisk bergart ved Kviteberg, Lyngen, Nord-Norge.

Det området som er beskrevet er på østsiden av Lyngenhalvøya ved Lyngseidet, 69° 35′ N og 20° 18′ Ø (Greenwich meridian). I de metamorfoserte sedimenter øst for Lyngengabbroen forekommer ultrabasiske bergarter ved Sandviken og Kviteberg (Pettersen, 1891). Det ultrabasiske legeme ved Kviteberg og de omgivende bergarter er diskutert i denne avhandlingen.

Den ultrabasiske bergart består av enstatitt og olivin med Mg-rik aktinolitt, spinel, magnetitt, svovelkis og i ett tilfelle diopsid som accessoriske mineraler, og serpentin, antofylitt, flogopitt, talk og kalkspat som sekundære mineraler. Dolomitt er vanligvis til stede og burde regnes for å være essensiell. Mikrosteksturen er mellom- til grovkornet hypautomorf.

De omgivende bergarter er fra Rottenvik østover mot ultrabasitten: 1, granatrik biotitt-hornblende skifer; 2, dolomitt med hvit diopsid i enkelte krystaller (opp til 40 cm × 20 cm) og i linser og masser (fig. 1); 3, en båndet serie med skifer og dolomit, den siste nærmest det ultrabasiske legeme. Så følger ultrabasitten med gradvise overganger til uren dolomitt på begge sider. Øst for dolomitten har man: 4, en dolomitt med skarnbånd og linser (ca. 13 m tykk); 5, granatførende biotittkvarts skifer med «øyer» av plagioklas og kalifeltspat (15 m tykk); 6, en båndet serie med amfibolittskifer, feltspatrik skifer med tynne konglomeratlag, båndete skifre med dolomittlag og diopsidrik skarn og en basal, massiv dolomitt (5½ m tykk); 7, varierte granatrike amfibol-kvarts-plagioklasskifre; og 8, mikroklin-biotitt-kvarts-granat-muskovitt-plagioklasgneis.

Strøket i området varierer mellom N 20 V og N 10 Ø og fallet er alltid mot V. I den vestlige delen av området er fallet ca. 40^{g} og i den østlige delen ca. 25^{g}.

Overfolding mot ØSØ er blitt iakttatt to steder, i dolomitten med aksefall 20^g mot S 20 V (fig. 3) og i skiferen nord for Kviteberg med aksefall 20^g mot S 15 Ø. Her sees også et skyveplan med strøk N 5 V og fall 15^g V (fig. 4, a og b). Overfoldningene og skyvningene står sikkert i forbindelse med den kaledonske orogenese. Kontaktene mellom ultrabasitten og de omgivende bergarter er konforme (fig. 5) og ultrabasitten er selv helt massiv.

To mulige dannelsesmåter må tas i betraktning. De er: 1, intrusjon av et ultrabasisk magma som krystalliserte på stedet; og 2, dannelse ved metamorf differensiasjon.

Barth (1926, 1930) har diskutert den første i forbindelse med sagvanditt fra ca. 60 km SV for Kviteberg, og det essensielle ved den metamorfe differensiasjonsprosess er å finne i, f. eks., Barth (1952, s. 317, 318) og Ramberg 1952, s. 215—220).

Vi foretrekker å tro at den ultrabasiske bergart ved Kviteberg er et metamorft differensiat, fordi denne teorien kan forklare strukturene i området, beliggenheten av ultrabasitten, sammensetningen av ultrabasitten, de gradvise overgangene til sidebergartene, og den store mengden av sekundær kalkspat i området. Ikke alle disse iakttagelser lar seg forene med den magmatiske teori.

Kvitebergområdets geologiske historie kan sammenfattes slik: Først ble området metamorfosert, og krystallinsk dolomitt, skifre og gneiser ble dannet. Så ble det deformert, lokalt ganske sterkt, og den ultrabasiske bergart ble dannet i en sone med ekstremt trykk. Deretter kom en periode med jevn kompresjon; skarnlag og ultrabasitten ble boudinagert og en del omkrystallisering fant sted, og kalkspat ble fordelt over hele området slik at den opptrer som bitte små intergranulære korn og i sprekker i andre mineraler.

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