GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN NO. 49

# SHEETING AND EXFOLIATION IN THE GRANITES OF SERMERSÔQ, SOUTH GREENLAND

BY

OEN ING SOEN

WITH 9 FIGURES IN THE TEXT

*Reprinted from*
*Meddelelser om Grønland, Bd. 179, Nr. 6*

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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## Abstract.

A study of sheeting structures in post-tectonic granites on the island of Sermersôq indicates that:

1) sheeting in the Precambrian granites of Sermersôq occurred mainly, if not exclusively, at the end of a second glacial stage on that island, i.e. during the Pleistocene;

2) this recent large-scale sheeting must have occurred spontaneously in a geologically speaking very short time interval;

3) there is no relation between the recent sheeting at a niveau immediately below the high-level erosion surface on Sermersôq and the removal of rock load above this surface by erosion; the latter erosion surface was formed in pre-Tertiary, Mesozoic or possibly Paleozoic times;

4) there are no relations between sheeting and primary structures in the granite;

5) the relation between sheeting and the most recent glacial geomorphological forms is very conspicuous;

6) sheeting has affected granites which were free or very poor in pre-existing open joints; the majority of all types of joints in the relevant granites were not opened before the period of spontaneous sheeting;

7) the cause of sheeting cannot be exclusively attributed to textural or compositional characteristics of the rocks;

8) sheeted granites in recently deglaciated areas may represent an early stage in the process of granite disintegration, which tends to the formation of a mature granite landscape with typical woolsacks and/or spheroidally exfoliated boulders.

A review of the literature indicates that the following relations exist:

a) large-scale deep sheeting, widespread exfoliation of boulders, and woolsacks are frequently associated phenomena characteristic of post-tectonic granites; the same combination of phenomena may occur in other rock types only when spatially associated with post-tectonic granite massifs;

b) large-scale sheeting in granite areas is commonly preceded by regional uplift.

A general inquiry into the cause and origin of sheeting and exfoliation leads to the following conclusions:

Insolation, weathering, climatological conditions, textural and compositional properties of the rocks are secondary factors in causing the large-scale sheeting of rocks. Dilatation subsequent to release of pressures is the main cause of sheeting and exfoliation. However, the compressive pressures are not mainly due to overlying rock loads and the release of pressures is not exclusively or mainly due to the removal of superincumbent rock load by erosion. The inadequacy of the current "load pressures and relief of load by erosion" hypothesis is discussed especially with regard to conditions on Sermersôq. Large-scale sheeting and widespread exfoliation are

related to an inherent property of post-tectonic granite massifs. Due to the mass deficiency represented by these massifs, gravitational body forces tending to raise the deficient masses above their surroundings originate, and during longer times these forces keep exerting an axial compression on the higher levels of the granites and the overlying or immediately adjoining country rocks. During epeirogenic uplift the vertically working forces are temporarily augmented by the epeirogenic forces, while subsequently the actual elevation of the area and the contemporaneous up-doming of the granites tend to compensate the existing gravitational anomalies and to reduce the gravitational body forces. Thus, when regional uplift ceases or slows down temporarily, a relative decompression of the combined gravitational and epeirogenic forces occurs rapidly, which enables the rocks near the surface to exfoliate spontaneously by dilatation in a direction normal to the free surface or topography.

Author's Address: Dr. OEN ING SOEN, Geologisch Instituut
der Universiteit van Amsterdam, Amsterdam.

# CONTENTS

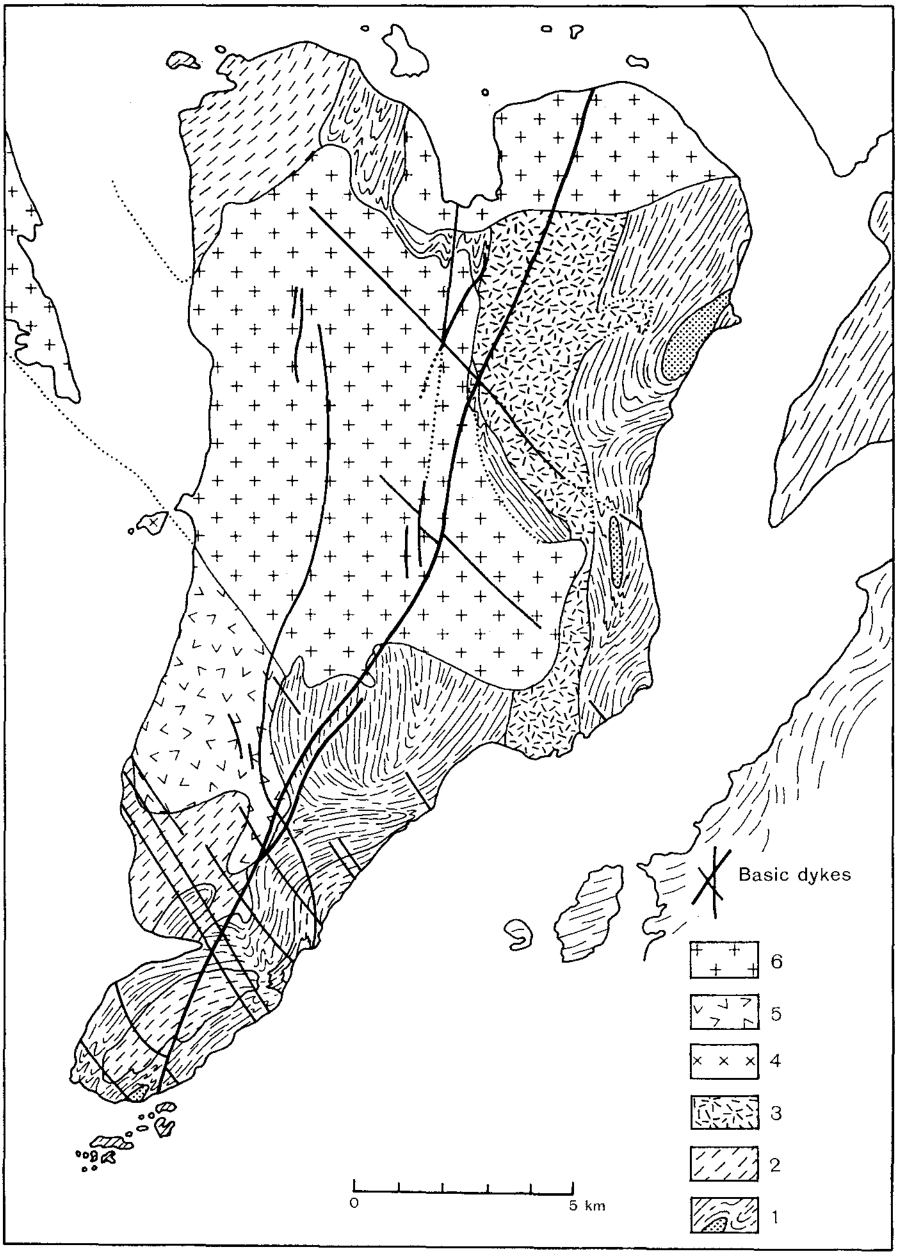


Fig. 1. Geological sketch map of Sermersôq. 1. Gneisses and mica schists with intercalations of granitic rocks (stippled). 2. Porphyroblastic granitic gneiss. 3–6. The younger granites. 3. Medium-grained foliated granite. 4. Coarsely porphyritic dark granite. 5. Coarse-grained porphyritic granite. 6. Coarse-grained coarsely porphyritic granite ("new granite").

# I. INTRODUCTION

Among the Precambrian granites, gneisses, migmatites and mica-schists on the island of Sermersôq in South Greenland a coarse-grained coarse-porphyritic granite, also designated as the "new granite", is extensively developed (Fig. 1). The areal extension of this granite in S Greenland is not as yet exactly known, but it occupies much larger areas than suggested by WEGMANN's (1938, p. 107) sketch map of the Sydprøven massifs, which include the coarse-grained coarse-porphyritic granite of Sermersôq and surrounding regions (BRIDGWATER 1963). This granite is considered to belong to a suite of Precambrian post-tectonic granites and syenites. On Sermersôq this "new granite" forms the latest member of a suite of younger granites, which furthermore includes a coarse-grained porphyritic granite, a foliated medium-grained granite, and a coarsely porphyritic dark granite (Fig. 1).

Older granitic rocks occur concordantly intercalated in the series of gneisses, migmatites and mica-schists, which form a framework of older, strongly folded and metamorphosed rocks, into which the younger discordant granites have intruded.

The petrology of Sermersôq will be dealt with in forthcoming papers and the present report concerns only observations on exfoliation joints or sheet structure in the granites and associated rocks. The "new granite" and the coarse-grained porphyritic granite exhibit a well developed sheeting whereby the rocks are broken into large curved sheets, roughly parallel to the topography. This feature has attracted the attention and interest of the geologists engaged in mapping the area for the Geological Survey of Greenland (see BRIDGWATER 1963, p. 175). This report is the author's contribution to the discussion on the subject.

The author is much indebted to all his colleagues of Grønlands Geologiske Undersøgelse for many stimulating and beneficial discussions, to Mr. K. ELLITSGAARD-RASMUSSEN, director of the Survey, for various facilities, to Dr. J. H. ALLAART, D. BRIDGWATER, T. C. R. PULVERTAFT, and A. WEIDICK for reading the manuscript, and to P. DAWES for companionship in the field. Dr. A. L. SIMONS, University of Amsterdam, has given valuable comments on the text of Chapter II. Miss A. VAN ARKEL kindly typed the manuscript.

# II. SUMMARY OF THE GEOMORPHOLOGICAL DEVELOPMENT OF SERMERSÔQ

The geomorphology of Sermersôq is the subject of a separate paper by the author (OEN, in press), and only the main conclusions will be repeated here to provide a base for discussing the relations between land forms and sheeting.

On Sermersôq the remnants of four erosion surfaces have been recognized: the high-level erosion surface at altitudes around 1000 m or higher, the intermediate-level erosion surface between 400 m and 650 m, the low-level erosion surface between 100 m and 250 m, and the strandflat, a coastal platform below 50 m. The development of these surfaces is believed to be related to three cycles of erosion, interrupted by two glacial stages.

A first, pre-Tertiary cycle of erosion had resulted in the formation of a peneplane, the uplift of which in late Cretaceous or early Tertiary times initiated a second erosion cycle. In this period of active uplift rejuvenated fluvial erosion rapidly dissected the uplifted peneplane, forming deep valleys, between which parts of the old erosion surface were locally preserved as high areas. After the onset of Pleistocene continental glaciation these high areas were situated above the snow line and were further conserved under a protective ice cover, while the deep, main river valleys became occupied by large glaciers coming from the inland areas. In the course of the subsequent development the ice-level in the fjords and bordering seas acted as the effective base level of erosion for the coastal regions situated between these main valleys (the present fjords). The areas above this ice-level but below the snow line remained subject to subaerial erosion tending to lower these areas to the niveau of the effective base level of erosion. At the height of this first and apparently main glacial stage these lowered areas were eventually overflown by the ice. After the latter had retreated stretches of a mammilated, planated surface, remnants of which are now found as the intermediate-level erosion surface, were left at altitudes corresponding roughly to the former effective base level.

The beginning of the subsequent interglacial stage was marked by a relatively sudden drop of some hundred meters in effective base level of erosion; that is from the former ice-level in the main valleys to the interglacial sea-level. This event initiated a third fluvial erosion cycle. The altitude of the strandflat is believed to correspond with the interglacial sea-level. The formation of this coastal platform presumably started at the end of the main glacial stage and continued during the further course of the third cycle of erosion until its comparatively recent emergence. The low-level erosion surface, a gently coastward sloping terrace, is believed to have been formed also mainly during this interglacial by subaerial erosion.

During the interglacial stage some of the ice-abandoned valleys on Sermersôq appeared as hanging glacial valleys and the knickpoints existing at their mouths were rapidly displaced headward by the rejuvenated fluvial erosion. In the further course of the third cycle of erosion a second glacial stage with the localized character of a mountain glaciation intervened; the valleys with headlands in the elevated interior parts of Sermersôq were then again glaciated and the knickpoints were modified by glacial action, leaving steps in the valleys. The valleys on Sermersôq, which are characterized by these steps occurring at approximately the same distances from the main valleys (the present main fjords), and by debouchures at the level of the strandflat (interglacial sea-level) are referred to as the younger valleys in a morphological sense, because of their typical immature interglacial forms, glacially modified during the second glacial stage. On the other hand, the valleys, the headlands of which had been previously lowered to the level of the intermediate-level erosion surface, were not glaciated during the latter period and river erosion continued, causing the recession of the valley's headwalls. The latter valleys show older glacial forms and differ from the younger valleys by stronger fluvial modification of the glacial forms, by more graded valley floors and the absence of steps or knickpoints. In another group of valleys, situated in a favourable northward-facing position, the glaciers apparently persisted during most of the time from the main glacial stage up to the present (e.g. the Napassorssuaq glacier). The latter valleys also do not show the immature fluvial forms of the younger valleys because they have not been subjected to the interglacial fluvial cycle.

During the mountain glaciation of the second glacial stage favourable conditions for effective cirque erosion existed. Rapid cirque recession caused the enlargement of cirques resulting in the present day fretted upland morphology of central Sermersôq, characterized by broad cirque floors with sharp peaks and ridges in between them. The retreat of the snow line with the recent waning of glacial conditions has locally given rise to the formation of cirque stairways.

Post-glacial vertical movements causing the emergence of the strand-flat induced a rejuvenation and consequently the incision of this coastal platform and of the glacial valley floors by the recent rivers and torrents.

For the discussions to follow it is important to note that two of the most striking morphological characteristics, the fretted uplands of central Sermersôq and the younger glacial valleys, have been formed during the second glacial stage in the course of the third or most recent cycle of erosion.

# III. THE DEVELOPMENT OF SHEETING STRUCTURES ON SERMERSÔQ

## 1. Introductory remarks.

In a formal descriptive sense the term exfoliation denotes all those structures in rock masses, which consist of a series of curved shells or sheets parallel to the surface of the rock mass. However, a kind of large-scale exfoliation, which appears particularly characteristic of certain granite mountains, has often been specially referred to as hypogene exfoliation, pseudo-bedding, or sheeting. Some writers have clearly distinguished between this type of sheeting and exfoliation on a smaller scale. BLACKWELDER (1925, p. 795), writing on exfoliation as a phase in rock weathering, found it necessary to state that: "Merely curved joints are not true exfoliate structures. For this reason I think it unnecessary to consider here the origin of sheeting structure in granite and the dome-shaped joints of such regions as the Yosemite Valley in California. Whether these be due to the relief of compression through erosion, as suggested by G. K. GILBERT, or to some other cause, they are structures of larger order of magnitude than the exfoliation of individual joint blocks". JAHNS (1943, p. 80), writing on sheet structure in granites remarked that: "It should be borne in mind, moreover, that sheet structure is a feature distinctly different in origin and significance from the "exfoliation" of spheroidally weathered rock masses". DODGE (1947, p. 38) and BRADLEY (1963) have also made similar distinctions between large-scale sheeting and small-scale exfoliation.

The distinction between sheeting and exfoliation made above may appear merely a question of scale; transitions may exist and in practice it may be difficult to differentiate between them. However, from a genetic point of view the distinction appears important. Many writers have found strong evidence for attributing the small-scale exfoliation of boulders and joint blocks to the action of weathering or of insolation, whereas many observers have proved that large-scale sheeting of granite masses is not bound to any climatic zone, that it occurs in unweathered rocks, and that it extends to depths far beyond those to which weathering and insolation could possibly be effective (see chapter IV). Obviously the latter kind of sheeting cannot be explained by references to arguments and conclusions which are valid only for the small-scale exfoliation of boulders and joint blocks at the earth's surface. This being realized, not much ground would be left for ascribing large-scale sheeting in granites to insolation and/or chemical weathering as some authors still maintain (chapter IV).

From a genetic point of view sheeting should also be distinguished from primary and tectonically imposed joints in the granites. Sheeting in a granite is the splitting off of the granite mass into sheets parallel to the topography; thus, sheeting should be a secondary feature occurring after the development of the topography. However, certain primary joints in granite, as e.g., primary flat-lying joints (CLOOS 1925, chapter IV: Lager und Bankung; BALK 1937), and joints due to the cooling and contraction of granite masses often exert a controlling influence on the topography resulting in a parallelism of jointing and topography. Confusion of sheeting with primary joints apparently led some earlier authors (e.g., VOGT 1879; OXAAL 1916) to ascribe a primary origin to sheeting; LJUNGNER (1930, p. 80) has shown that in the regions described by these authors there are two types of "Bankung", one older than the present topography and another one which is dependent on the topography and unrelated to other structures in the granite. Obviously only the latter type of jointing is to be considered as sheeting.

It appears that the recognition of sheeting structures may become difficult especially in those regions without pronounced landscape forms and where sheeting occurs together with small-scale superficial exfoliation and/or with primary and tectonic joints. Sheeting as described in this paper from Sermersôq refers to a large-scale exfoliation which appears typical for certain granite massifs and which bears the following main characteristics:

1) it extends to depths beyond those to which weathering and insolation could possibly be effective;
2) it has clearly developed later than the topography and is dependent on the glacial geomorphological forms;
3) the planes of sheeting are generally parallel curved planes whose disposition is totally unrelated to primary features of the granite;
4) aplites, pegmatites, and other veins are absent along the planes of sheeting; displacements along planes of sheeting, other than those caused by recent creep, have not been observed;
5) a well developed sheeting occurs only in rocks poor in pre-existing open joints;
6) the thickness of the exfoliated sheets in general increases from the surface downwards, varying between a few dm to about 2 m.

Fig. 2. Sheeting in the "new granite" along the Qôrorssuasik valley, E Sermersôq. The sheeting structures are seen in the central part of the photograph. The mica schists in the background (left-hand side of picture) and the "new granite" with abundant large inclusions in the foreground (right-hand side of picture) are devoid of sheeting structures.

## 2. The relation between sheeting and topographical forms.

The planes of sheeting in the granites on Sermersôq clearly follow the glacial topographical forms of the third and most recent cycle of erosion.

Sheeting in the steep walls of older as well as younger glacial valleys occurs along steep, gently curved planes parallel to the valley walls (Figs. 2 and 3), while in the broad valley and cirque floors subhorizontal sheets, either somewhat concave or convex towards the sky, have frequently been observed. In cirque walls sheeting occurs along steep planes characteristically concave towards the sky (Figs. 5 and 6). In peaks and horns sheeting is nearly vertical (Figs. 3 and 5). In gently sloping, rounded mountains and hills the sheet structures show dome-shaped patterns (Figs. 6, 7, 8 and 9). The latter hills have been considered as relics of a subdued pre-glacial landscape (Oen, in press); where these hills have been affected by later cirque erosion a typical intersecting of concave and convex forms has resulted and the sheeting strikingly conforms to these typical forms (Fig. 6). Along steep coasts sheeting along steep, slightly curved planes is also often noted.

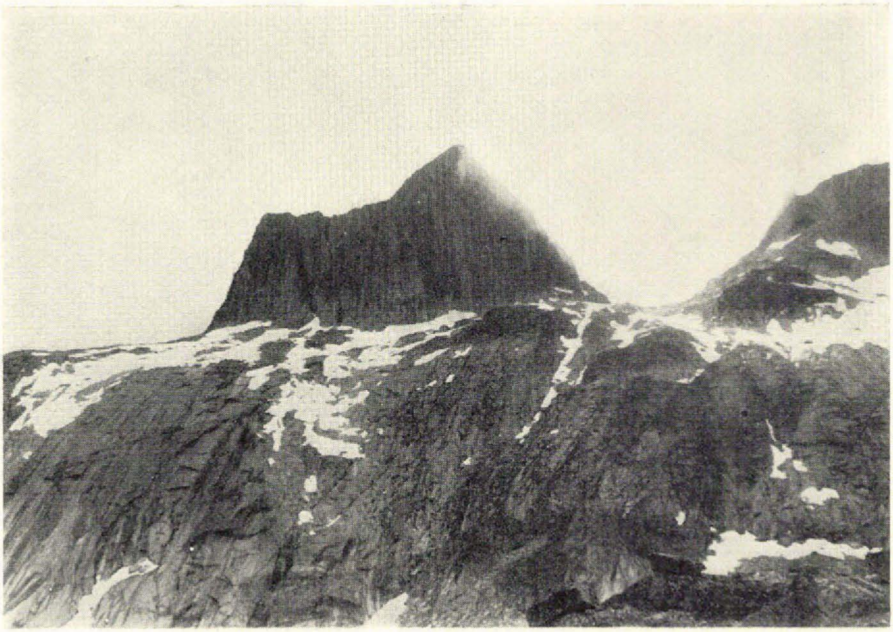

Fig. 3. Sheeting in the "new granite" along the western wall of the Napassorssuaq valley. The planes of sheeting are parallel to the valley wall. The vertical planes in the sheeted granite are planes of parting. Vertical jointing is absent in the sheeted granite, but some inclined master joints occur. In the background is a steep mountain with approximately vertical joints and devoid of the typical curved planes of sheeting.

Sheeting is generally best developed at places of strong topographical relief due to the younger glacial valleys and fretted upland morphology of the second glacial stage. On the plateaus, the remnants of older erosion surfaces, sheeting is usually not well developed, absent, or possibly unexposed.

The glacial morphology of Sermersôq shows a typical development in complete concordance with the morphology of other glaciated regions where no sheeting occurs. Therefore, it is evident in the present case that the sheeting must have developed consequent to the glacial sculpture of the landscape. For example, the straight glacial valleys and straight coast lines have evidently developed independent of the sheeting, for if they were influenced by the latter they would rather show irregular or sinuous courses. The accordance of the planes of sheeting with features of dissection in the morphology (glacial valleys) has already been put forward by GILBERT (1904) as an argument for the secondary nature of the sheeting in California, U.S.A. VOGT (1879) also already noted the striking parallelism of sheeting in granites and the fjord topography in Norway, while HARLAND (1957) mentioned sheeting in some alpine glacial valleys.

Fig. 4. The left-hand side of the photograph shows the Qôrorssuasik valley (Fig. 2). In the center of the figure is a glacial cirque excavated in the "new granite"; sheeting in the latter is parallel to the cirque walls.

## 3. The age of the sheeting structures.

Since sheeting follows the relief determined by the younger glacial valleys and fretted upland morphology, it follows that the sheeting must have originated after the beginning of the second glacial stage on Sermersôq (chapter II). During this stage blocks of "new granite", loosened along planes of sheeting, were carried down the valleys by the glaciers in the younger glacial valleys and deposited near the valley mouths to form large end-moraines. On the other hand, the upstream parts of the valleys and their cirques appear remarkably cleaned of loosened blocks, so that no appreciable sheeting and loosening of blocks seems to have occurred after the retreat or disappearance of the glaciers. On more gentle slopes, which were not directly affected by the transporting agencies of glacial erosion, boulder accumulations still appear, and also along the foot of steeper slopes. Matthes (1930) has described similar relations from the Yosemite region in California, where granite masses were stripped of all their exfoliated sheets by the overriding Merced glacier of the Wisconsin stage, but still show no signs of renewed sheeting over the greater part of their surface. Kieslinger (1958, 1960) made similar observations in Norway.

Matthes and Kieslinger have concluded that the sheeting in the areas described by them is pre-glacial in age. However, on Sermersôq the major part of the sheeting structures apparently have developed after the geomorphological forms of the second glacial stage have acquired their present shapes, but before the glaciers in the younger glacial valleys have vanished. Therefore, it is concluded that sheeting in the

Precambrian granites of Sermersôq occurred mainly, if not exclusively, at the end of the second glacial stage, that is spontaneously in a geologically speaking very short time interval.

Intersecting or superposition of different generations of sheeting has not been observed and, therefore, the sheeting parallel to older morphological features, such as the subdued pre-glacial hills or the older glacial valleys, most probably belongs to the same generation as the sheeting parallel to the younger morphological forms of the second glacial stage.

Moreover, it follows from the above that the sheeting which occurs at a niveau immediately below the high-level erosion surface on Sermersôq, is much younger than the latter surface. The rocks originally overlying this surface had been largely removed before the late Cretaceous or early Tertiary uplifts. The recent large-scale spontaneous sheeting in the elevated mountains was preceded by a significant uplift but not by an appreciable removal of rock load above the niveau of sheeting. But, although the large-scale removal of rock load by erosion cannot in the present case be considered as a fundamental cause of sheeting, the localization of sheeting structures along steep topographical features due to the dissection of the uplifted high-level erosion surface suggests that these younger features of erosion have in fact exerted a controlling influence on the distribution of sheeting structures in the area. SCHEIDEGGER (1963, p. 83) has stated that when a valley is cut into an area in which as usual a stress system is present, then the adjustment of the stresses to satisfy the boundary conditions at the surface (where the normal stress must be zero) may cause stress concentrations in certain areas, which may become so large that the rock fails, so that it develops sheeting structures as it becomes exposed. According to this line of thought it also follows that sheeting on Sermersôq occurred consequent to the incision of the younger glacial valleys.

## 4. The relation between sheeting and primary structures in the granites.

The "new granite", which shows the best developed sheeting of all granites on Sermersôq, is poor in primary structures. The granite has mostly a massive structure, and only locally does the planar orientation of the abundant potash feldspar megacrysts define a conspicuous foliation, especially near granite contacts and large inclusions. This foliation tends to be parallel to the granite contacts and is unrelated to the attitude of the planes of sheeting.

The "new granite" is bounded by well exposed sharp, usually vertical or steeply outward- or inward-dipping contacts. The pattern of straight granite contacts strongly suggests a control of the shape of the granite by pre-intrusive fractures or faults. The roof of the "new granite" seems nowhere observable on Sermersôq. Evidently the disposition and distribution of sheeting in the "new granite" are completely unrelated to the shape or contacts of the granite.

Fig. 5. A glacial cirque in the "new granite" of central Sermersôq. The planes of sheeting are parallel to the cirque walls. The curved planes of sheeting seem to merge into the vertical joints in the peak seen in the upper left-hand corner of the figure. The peak is 1240 m high, the cirque floor is at about 600 m.

At several places the "new granite" contains large inclusions of schist or gneiss, often several tens of meters long. Where such inclusions are abundant sheeting is a rule not or only very poorly developed.

Sheeting is also absent or poorly developed at places where vertical joints probably of tectonic origin are important (see next section). Primary joints formed in connection with the intrusion and consolidation of the granite magma, may possibly be present locally in the "new granite", but they have not been recognized as such. The only discernible relation between sheeting and other jointing in the granite seems to be that they tend to exclude each other.

Other primary structures of occasional occurrence in the "new granite" include a subhorizontal rhythmic mineral layering, irregular biotite schlieren and irregular trains of small inclusions. All these features do not appear to be related with the sheeting in the granite.

## 5. The relation between sheeting and vertical or other joints in the granites.

There are two directions of important joint systems on Sermersôq; these are: $s_1$) ENE–WSW, around E–W, to WNW–ESE, and $s_2$) NNE–SSW, around N–S, to NNW–SSE. The direction $s_2$ is less pronounced than $s_1$. The majority of these joints are vertical, but inclined joints along the same directions also occur. The two joint directions are of constant and regional development in all rocks on Sermersôq, especially in the schists, gneisses, and the foliated medium-grained granite. Vertical and inclined master joints generally transect the boundaries between the different rocks.

The occasional presence of pegmatitic, aplitic or quartz veins along some of the joints indicates their origin in older periods. Veins occurring along joints of the one joint set often appear displaced along the direction of the other joint set, suggesting a possible origin as shear joints. Pegmatites and aplites along joints in the coarse-grained porphyritic granite in central W Sermersôq (Fig. 1) are cut off by the contact-planes of this granite and the younger "new granite", which indicates the prevalence of the stress pattern causing the $s_1$ and $s_2$ joint systems already before the emplacement of the "new granite". However, the occurrence of the same joint sets in the latter granite also indicates a continuation of the same stress pattern after the emplacement of the "new granite".

In the "new granite" there is a striking relation between the topographical forms and the development of sheeting and/or vertical joints:

a) In regions with pronounced topographic relief with strongly curved topographic planes, such as the glacial valley walls, the cirque walls, and steep dome-shaped mountains, the most beautiful sheeting occurs, while the nearly complete absence of vertical or other jointing is noteworthy (Figs. 2–9). The exfoliated sheets are broken along irregular surfaces of parting, approximately perpendicular to the planes of sheeting. Other directions of parting sometimes coincide with that of the

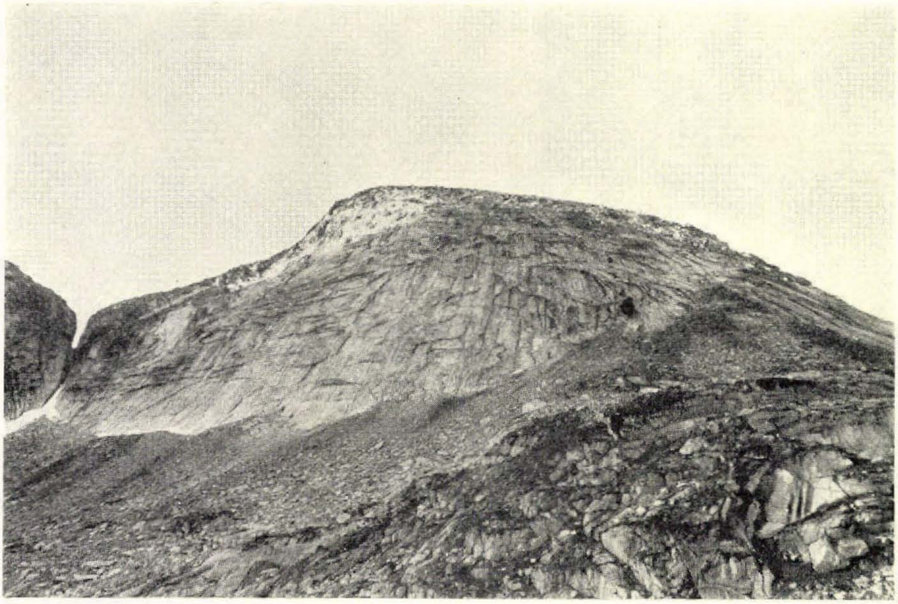

Fig. 6. Sheeting in the "new granite" SW of Kangerdlua bay, N Sermersôq. The top-area of the mountain (925 m) forms part of the high-level erosion surface and it shows a relic of the pre-glacial landscape forms characterized by subdued hills with slopes convex towards the sky (right-hand side of figure). The glacial cirque at the left-hand side is a younger morphological feature characterized by walls which are concave towards the sky. The superposition of younger on older morphological forms gives rise to a typical intersecting of convex and concave surfaces. The planes of sheeting in the glacial cirque are parallel to the cirque walls and concavely curved towards the sky, whereas the planes of sheeting parallel to the hill slopes at the right-hand side of the figure are convexly curved towards the sky. The concavely and convexly curved planes of sheeting do not intersect, which indicate that there is no superposition of younger planes of sheeting on older ones. This leads to the conclusion that the planes of sheeting parallel to the older convex forms are as recent as those parallel to the younger concave forms in the cirque, i.e., that all sheeting are of the same recent age. Furthermore, note the absence of other types of jointing in the sheeted granite and the development of the sheeting at a niveau immediately below the high-level erosion surface.

vertical joint directions elsewhere, but the planes of parting are distinguished from true joints by their irregular surface and by being discontinuous and usually restricted in their development to the thickness of one or two sheets. Obviously these partings have developed subsequent to the sheeting, presumably as a result of recent down-slope creep.

b) In strong contrast with the above is the well developed vertical jointing in many peaks and horns and along steep escarpments. Here sheeting is usually absent (Figs. 3 and 5).

Fig. 7. Sheeting in the "new granite" SW of Kangerdlua bay, N Sermersôq. The curved planes of sheeting are convex towards the sky and parallel to the slope of the mountain (1030 m). Sheeting is present immediately below the niveau of the high-level erosion surface. Note the absence of other types of jointing in the sheeted granite.

c) In areas without pronounced relief such as the plateaus, valley floors, and gently sloping hills both sheeting and vertical jointing are usually discernible, but in general none of them show a particularly good development.

Locally sharp junctions between areas with well developed sheeting along curved slopes and vertical jointing along vertical or steep escarpments have been noted (Figs. 3 and 5). The relations between topography, sheeting, and vertical jointing in the "new granite" indicate that at least the great majority of all joints have not been opened before recent times, about contemporaneous with the recent sheeting. Were this not the case, a superimposition of sheeting on jointed granite should be expected rather than their topographically controlled spatial separation. Thus, the recent sheeting has affected a granite which was previously devoid of or very poor in pre-existing open joints.

Observations in other regions in the world seem to confirm the inference that sheeting occurs in general only in rocks poor in pre-existing open joints (e.g., BRANNER 1896; GILBERT 1904; BALK 1939; MATTHES 1937; JAHNS 1943; KLAER 1956; HARLAND 1957; KIESLINGER 1958,

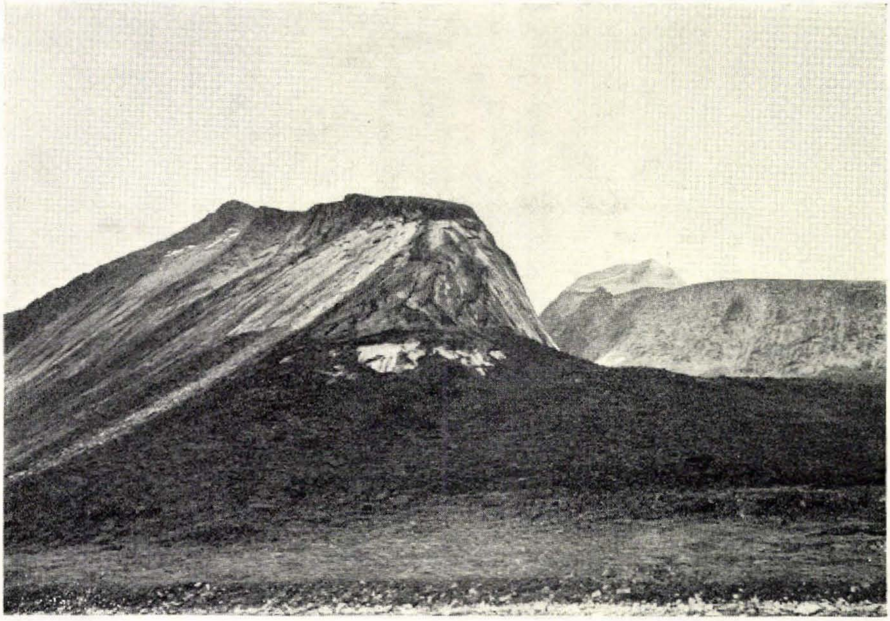

Fig. 8. Sheeting in the "new granite" on NE Sermersôq viewed from the NE. The planes of sheeting show a striking parallelism to morphological forms of different age. The crests of the high ridges seen in the figure are remnants of the high-level erosion surface. The ridge of foliated granite in the background does not show as good a sheeting as the ridge of "new granite" in the center of the figure. At the crest of the latter ridge the planes of sheeting approach a subhorizontal attitude (see Fig. 9). At the W side (right-hand side of photograph) this ridge is bounded by a younger glacial valley and the planes of sheeting are there parallel to the steep valley walls. At the E side (left-hand side of photograph), where the mountain is bordered by a fjord, the planes of sheeting are also parallel to the slope of the mountain. The nearly flat top of the lower hill in the foreground belongs to the low-level erosion surface; this hill shows nearly flat-lying planes of sheeting at the top and gently sloping, convexly curved ones at the flanks. Note especially the behaviour of the planes of sheeting in the center of the figure where the W- and E-flank of the ridge meet; the planes of sheeting keep conforming to the topography and consequently their strike bend around the corner formed by the ridge. The sheeting parallel to the older morphological forms is continuous with the sheeting parallel to the younger forms and they do not intersect each other; therefore, they belong to one generation which has developed after the younger morphological forms.

1960a, b). This seems particularly well demonstrable in recently deglaciated areas as the Greenlandic coasts, Scandinavia (Kieslinger 1958, 1960a, b), and the Yosemite region in California (Gilbert 1904; Matthes 1930). In regions with an older and less pronounced relief as e.g., in Central Germany (Meinecke 1957) and in N Portugal (Oen 1958), sheeting in the granites is mostly accompanied by other jointing and woolsack formation. The inference that older latent joints in granites

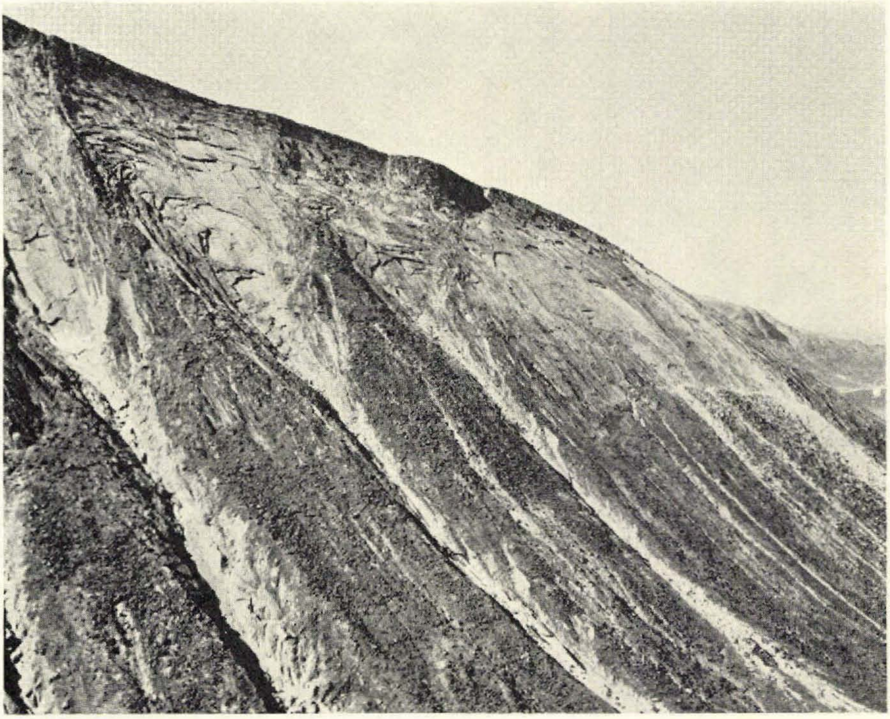

Fig. 9. Detail of the E slope of the ridge of "new granite" seen in Fig. 8. The planes of sheeting are convex towards the sky and approach a subhorizontal attitude near the crest of the ridge.
(Photo K. Ellitsgaard-Rasmussen)

were apparently not opened before sheeting occurred suggests that most of the jointing in the sheeted granites in the latter-mentioned regions might have been opened after sheeting has occurred (see further p. 24).

### 6. The relations between sheeting and rock types.

Sheeting on Sermersôq is decidedly much better developed in the "new granite" and in the coarse-grained porphyritic granite than in the other rock types. The foliated medium-grained granite locally shows a tendency to develop a good sheeting. Sheeting has not been observed in the schists or in the gneisses with pronounced gneissose structures. However, strips of gneissic rocks intercalated between masses of "new granite" sometimes display as good a sheeting as in the granite, especially where they have acquired a hornfelsic aspect due to contact-metamorphism. An example is afforded by the hornfelsic gneisses south of Kangerdlua bay, N Sermersôq, which in their sheeting so much resemble the enclosing granites that they were first erroneously mapped as such.

The common occurrence of sheeting in granitic rocks appears clearly from a survey of the literature. Indeed, large-scale sheeting has most frequently, if not exclusively, been described from regions where large granite massifs outcrop, e.g., the Sierra Nevada in California, U.S.A. (Whitney 1865; Gilbert 1904; Matthes 1930, 1937), New England and the Adirondack Mountains, U.S.A. (Dale 1923; Balk 1939; Jahns 1943), Maine, U.S.A. (Chapman and Rioux 1958), Brazil (Branner 1896), Cornwall, England (Waters 1952), Scandinavia (Vogt 1879; Oxaal 1916; Ljungner 1930), Spain and Portugal (Lautensach 1950; Oen 1958; Rondeau 1958), the Sudan, Africa (Ruxton and Berry 1961), etc. Among the granitic rocks which may show well developed sheeting porphyritic biotite granites are common, but hornblendegranites, syenites, monzonites, gneissic and foliated granites, are also frequently sheeted. Thus, sheeting is displayed by a variety of igneous-looking acid rocks, showing significant variations in texture and composition, and therefore, sheeting cannot be exclusively attributed to the textural or compositional characteristics of rocks. Sheeting does occasionally also occur in other than these siliceous igneous-looking rocks: Branner (1896) describes sheeting in gneisses, Balk (1939) mentions a poorly developed sheeting in metamorphosed sediments and anorthosites, while sheeting in massive sandstones has been described by Bradley (1963) and also noted by Harland (1957). Observed and experimental evidence (Adams 1910; Bain 1931, 1938; Bridgman 1938; Lewis 1954; Kieslinger 1958) have demonstrated that massive limestones and other homogeneous substances may under certain circumstances exfoliate as easily as granites. Furthermore, the common occurrence of small-scale, spheroidal exfoliation structures in dolerites, diabases, and other basic igneous rocks indicates that, although these rocks are generally devoid of large-scale sheeting, the rock type itself is very liable to develop exfoliation structures.

On Sermersôq sheeted gneisses occur adjoining the post-tectonic "new granite". Similarly, it appears from the literature that where large-scale sheeting in gneisses and non-granitic rocks has been described, these rocks nearly always appear in spatial association with large granite massifs. Thus, there seems to be a spatial association between large-scale sheeting and the occurrence of certain granite massifs rather than any relation between large-scale sheeting and the compositional or textural characteristics of granitic rocks.

The conditions on Sermersôq suggest that sheeting in the gneisses may be conditioned by the presence of the post-tectonic "new granite", which itself shows the most perfect sheeting. In Portugal (Oen 1958) sheeting is best displayed in large batholiths of coarse-porphyritic biotite granites forming the youngest member of a series of post-tectonic granites; in the same country large massifs of older granites, considered as late-syntectonic granites, appear strikingly devoid of sheeting. Post-tectonic granite intrusions are represented in the Sierra Nevada and New England in the U.S.A., in Cornwall, England, and in most, if not all, of the other regions mentioned above. Therefore, it is tentatively suggested that sheeting is spatially associated with post-tectonic intrusive granite masses.

## 7. The association of sheeting with woolsack weathering and exfoliated boulders.

Sheeting in granites is frequently accompanied by a typical kind of granite weathering, which give rise to the formation of typically rounded boulders or woolsacks, sometimes of appreciable dimensions (BRANNER 1896; LAUTENSACH 1950; KLAER 1956; MEINECKE 1957; RONDEAU 1958; SCHATTNER 1961, etc.). Not infrequently the woolsacks show a spheroidal exfoliation parallel to their surface. Woolsack formation is usually ascribed to agencies of chemical and mechanical weathering, working along open joints and rounding off the originally angular edges of joint blocks.

The granites on Sermersôq do not in general show woolsack formation. Nevertheless, the "new granite" shows an obvious tendency to disintegrate rapidly into coarse sand, while transported boulders resembling woolsacks or showing tendencies to develop in that direction have sometimes been noted. In a few boulders a beginning of spheroidal exfoliation has been observed.

Although woolsacks with or without spheroidal exfoliation are different in scale as well as in origin from the sheeted dome-like granite mountains, their analogous form and frequent spatial association suggest a control by similar or nearly similar conditions and any attempt to explain sheeting must take account of this.

In woolsack weathering the climatic factor undoubtedly plays an important role. Blankets of coarse sand on the plateaus of "new granite" indicate a significant rate of mechanical weathering. However, chemical weathering seems ineffective or to operate so slowly that since the last deglaciation results are not to be expected. Nevertheless, the woolsack-like boulders on Sermersôq suggest that woolsacks may eventually form in the "new granite", provided sufficient time is available and other joints open in addition to the planes of sheeting.

The absence of woolsacks on Sermersôq and in other recently deglaciated areas of sheeted granite (Scandinavia, Yosemite region) contrasts with the abundant woolsacks in granite areas with an older exposed topographic relief. It is suggested that the sheeted granites in recently deglaciated areas represent an early stage in the process of granite disintegration, which tends to proceed towards a mature granite landscape with typical woolsacks; the rate of this process is apparently dependent on climate and other factors. The process implies the opening of older latent joints subsequent to the sheeting, and the rounding of joint blocks by weathering.

Granting that sheeting, spheroidal exfoliation of boulders and woolsacks, by their analogous form and common association must have a common cause, and that dilatation of rock masses subsequent on relief of pressures may be one such cause, it is believed that joint blocks and boulders exfoliate primarily along dilatation structures; the effects of weathering being very important but ultimately of secondary nature. Experiments and observations have indicated that dilatation and weathering may go hand in hand as mutually enhancing processes causing exfoliation (Griggs 1936; Farmin 1937). Similarly, the rounding of joint blocks into woolsacks may be mainly achieved by weathering, but ultimately governed by a latent exfoliation structure due to dilatation (Kieslinger 1958).

# IV. ON THE CAUSE AND ORIGIN OF SHEETING AND EXFOLIATION IN GRANITES

## 1. An evaluation of older and current hypothesis.

The various hypotheses on sheeting in granites have been reviewed, e.g., by BRANNER 1896; DALE 1923; LJUNGNER 1930; JAHNS 1943; and RONDEAU 1958. Sheeting in granites has been attributed to one or more of the following causes:

1) Contractional or tensional strains set up during cooling of a granite mass (e.g., VON ADRIAN 1863; WHITNEY 1865; VOGT 1879; OXAAL 1916; MEUNIER 1961).
2) Insolation due to solar heat or other temperature variations (e.g., SHALER 1869; MERILL 1906; KLAER 1956).
3) Weathering (e.g., HERMANN 1899; BLACKWELDER 1925, 1933; BARTON 1916, 1938; COTTON 1952; MEINECKE 1957).
4) Tectonic forces (e.g., DALE 1923; MEUNIER 1961).
5) Dilatation subsequent to release of confining pressures (e.g., GILBERT 1904; MATTHES 1930, 1937; FARMIN 1937; BALK 1939; VON ENGELN 1942; BILLINGS 1942; JAHNS 1943; WATERS 1952; LEWIS 1954; HARLAND 1957; CHAPMAN 1958; CHAPMAN and RIOUX 1958; KIESLINGER 1958, 1960a, b; RONDEAU 1958; SCHATTNER 1961; RUXTON and BERRY 1962; SCHEIDEGGER 1963; BRADLEY 1963).

In general the view that all sheeting is due to the cooling and contraction of igneous masses prevailed until about the end of last century; the insolation, weathering and tectonic hypotheses have found most adherents during the first decades of this century, while the dilatation or relaxation hypotheses are currently the most accepted ones.

The cooling of an igneous mass may produce parallel curved fractures resembling sheeting structures as, e.g., in the granites of Zinnwald, Silesia (OELSNER 1952, p. 22), and of Fort Lamy in the Sudan, Africa (BARBEAU and GEZE 1957). The presumed origin of these fractures implies their development independent of the topography and related to the form or contacts of the igneous body; they are likely to be accompanied by contemporaneous fractures perpendicular and oblique to the planes of cooling, and therefore also showing a relation to the shape of the igneous mass. In the Zinnwald granite for example, tin veins along the fractures indicate a fracturing during or following the consolidation of the granite. Contraction fractures conceivably may earlier have controlled the topography which is subsequently followed by the sheeting. In these cases confusion of contraction fractures with sheeting may easily result in a misinterpretation of the latter. However, sheeting differs from contraction fractures by its recent age, its relation to topographical forms and independence of older structures; these characteristics being discerned, an origin as contraction fractures can be precluded.

Insolation and weathering can under certain circumstances result in rock exfoliation. Numerous examples of exfoliation apparently caused by fires are known (Warth 1895; Högbom 1921; Blackwelder 1927; Emery 1944). The evidence of exfoliation by chemical weathering has been summarized, e.g., by Blackwelder 1925, 1933, and Chapman and Greenfield 1949. However, insolation and weathering cannot explain large-scale deep sheeting (p. 11). The reluctance of many authors to disregard these processes in considerations on large-scale sheeting may arise from the fact that small-scale superficial exfoliation of boulders and slopes by insolation and weathering frequently accompany deep sheeting. Alternatively, this association affords an argument to regard insolation and weathering merely as secondary factors, capable only of enhancing exfoliation in certain rocks and under certain circumstances.

Field observations do not in general suggest tectonic compression as a direct cause of sheeting. But obviously the spontaneous expansion of rocks as often observed in exposures and mines (Bain 1931, 1938) and in experiments (Adams 1910, Bridgman 1938) can occur only when the rocks were first suitably compressed. However, the compressive forces need not necessarily be tectonic forces. As noted earlier (p. 24) sheeting seems related to post-tectonic rather than syntectonic granites. Furthermore, in Bridgman's experiments diverse materials subjected to high confining pressures and still higher axial compression developed fractures at right angles to the direction of axial compression when the latter was released. Therefore, it seems that for the explanation of sheeting one has to look for a vertically operating axial compression in post-tectonic granites rather than for laterally working tectonic forces.

The hypothesis of dilatation of rocks subsequent on release of confining pressures, first proposed by Gilbert in 1904, is formulated by Harland (1957) as follows: ". . . . rock at depth is under general compression, and expands on the removal of overload. While this expansion may take place freely in a direction normal to the topographical surface, the rock is constrained in directions parallel to the surface. This results in relative compression parallel to the topographical surface, with consequent extension fracturing. Extension fracture, unlike shear fracture, allows the rock to expand in the direction of minimum principal stress by fractures normal to it." JAHNS (1943) mentions the evidence of compressive strain in quarries and natural exposures, the youthfulness of sheet structure with respect to primary structures in the granite and adjacent country rocks, the depths to which sheeting is known to extend, and the gradual downward changes in attitude and thickness of the sheets, as characteristic features entirely compatible with the above hypothesis. In spite of this, the adequacy of the hypothesis may be questioned on the following grounds.

Generally a relief of confining pressures by removal of superincumbent load is assumed. However, the conditions on Sermersôq suggest that the recent spontaneous sheeting at a niveau directly below the high-level erosion surface is unrelated to the removal of rocks above the latter surface (p. 16). The possibility of two generations of sheeting on Sermersôq, an older one conforming to the high-level erosion surface and developed after the removal of rock load and a younger one conforming to the topography after the second glacial stage and developed after the removal of ice load and of rocks by glacial erosion, seems remote in view of the fact that superposition of two systems of sheeting have not been observed and of the earlier conclusion that most joints in the granites (vertical joints, sheeting planes and other fractures) have not been opened before the recent spontaneous sheeting (p. 20). Moreover, if rapid removal of load pressures is the main cause of sheeting, one would expect the sheeting to be more extensively developed in the topographically lower areas, such as the strandflat. However on Sermersôq sheeting is most commonly found at higher topographical levels. Furthermore, the hypothesis does not explain why sheeting preferably, if not exclusively, occurs associated with post-tectonic granite massifs. Since other rock types seem as liable to exfoliation and sheeting as granites (p. 23), then if relief of confining pressures by removal of superincumbent load is the main cause of sheeting, there is no apparent reason why large-scale sheeting should be confined to post-tectonic granites and associated rocks and why it should not be a more general phenomenon in syntectonic granites and massive sandstones, limestones, and basic igneous rocks. This problem leads to an inquiry into the special properties of post-tectonic granite massifs, which may favour sheeting.

## 2. Uplift of post-tectonic granite massifs as a possible explanation of the sheeting structures associated with these massifs.

A geophysical study of the granite problem by Bott (1953, 1956) seems to contain the relevant information; it appears that:

a) negative gravity anomalies are normally found over post-tectonic granite masses[1];

b) these anomalies are caused by a direct density contrast (usually between 0.05 and 0.20 $g/cm^3$) between the less dense acid intrusion and the denser country rocks;

c) the negative anomalies are often of considerable size and represent mass deficiencies which extend to depths generally greater than 3000 m and up to 12000 m and more; the shape of the gravity anomalies in relation to granite outcrops demonstrate fairly steep contacts which sometimes slope outwards.

Bott (1956, pp. 59–60) further states that the gravitational body forces arising from such mass deficiencies in the upper crust tend to raise the region of the deficient mass at the expense of the surroundings. The response to the stress system will depend on whether or not the critical function of stresses required to initiate non-elastic behaviour (i. e. the strength) is exceeded, either in the granite or in the surrounding country rocks. Uplift of a granite mass of which the stress system is normally within the elastic range, may be possible under special circumstances when the strength is exceeded, either because it is lower than usual, or because external events increase the stress differences. The superposition of an external crustal stress system during periods of epeirogenic activity will alter the existing stresses and epeirogenic post-emplacement uplift of granite batholiths may thus be explained by an isostatic type of mechanism. The result of doming or uplift will be that the deficient mass is compensated by a surface load, which may be levelled by subsequent erosion to reintroduce the original stress differences.

The significance of the above with regard to the origin of sheeting in granites may now be evaluated by checking the consistency of a hypothesis which connects the sheeting structures in granites with the uplift of post-tectonic granite massifs.

i) Post-tectonic granite massifs consist of one or more granite bodies bounded by vertical or steep contacts and are of lower density than

[1] For other examples of negative gravity anomalies associated with granite masses see Romberg and Barnes (1944), Garland (1950, 1953), and Smithson (1961).

the surrounding rocks. The gravitational body forces arising from the mass deficiency tend to raise the granites above their surroundings, but the resulting stresses normally remain below that necessary to cause their actual uplift. However, as the forces remain operative, the higher levels of the batholith and its overlying and directly adjoining country rocks will remain under effective vertical compression, i.e., the kind of compression that fulfills the requirements stated on p. 27.

ii) During periods of epeirogeny the superposition of epeirogenic and gravitational forces may temporarily augment the existing stresses and eventually cause updoming of the granites above their surroundings. Model studies of salt-dome tectonics (PARKER and McDOWELL 1955) show that when a critical value of overburden is exceeded doming cannot occur; therefore, removal of overlying rocks by erosion apparently favours the possibility of updoming of the granite masses. The author (OEN 1960) has shown that in N Portugal an axis of post-Hercynian and recent uplifts coincides with an axis of Hercynian post-tectonic granites. Other examples of post-emplacement epeirogenic uplift of granites are cited by BOTT (1956, p. 59), while attention may also be drawn to WASHINGTON's law, formulated by BUCHER as follows: "for large units of the earth's surface, the average density of the exposed igneous rocks varies roughly with the inverse of the average altitude" (WASHINGTON 1922, BUCHER 1933). Even in the case that updoming of the granites above their surroundings is not demonstrable, the expected result of epeirogenic uplift is a temporary augmentation of the vertically working stresses. After the cessation of the uplift, these will drop below the value before the uplift, because uplift tends to compensate the gravitational anomalies and to reduce the gravitational forces. Therefore, a relative decompression directly subsequent to regional uplift can be conceived.

iii) In many regions where sheeting in granite is a widespread phenomenon a recent uplift has been demonstrated, e.g., in South Greenland, Portugal, Scandinavia, the Yosemite region (AXELROD 1962), Brazil (MEUNIER 1961), etc.. KING (1949), who also noted the close association of bornhardts, exfoliation of the "relief of load" type, and plutonic rocks, has confirmed the observations of OBST (1923), according to whom the mentioned phenomena are found only where there are traces of two cycles of erosion, i.e., indications of a new, more recent uplift, without which bornhardts cannot occur. Thus, the expected consistent relation between regional uplift and subsequent sheeting seems demonstrated.

iv) The vertical compression exerted in the upper crust by the gravitational body forces of a deficient granite mass at comparatively shallow depths is evidently much smaller than the vertical compression exerted at greater depths by the weight of a pile of several kilometres of superincumbent rocks. However, the present hypothesis implies that sufficient effective vertical compression may be assumed as the combined and additive result of upward directed gravitational and epeirogenic forces. Yet, the reason why the present hypothesis seems more adequate than the "load pressures and relief of load by erosion" hypothesis should still be elucidated.

Bradley (1963, p. 524) has recently written: "Fracture of rocks in fresh quarries and tunnels, in high pressure laboratory experiments, and in deep cores brought to the surface indicated that when stresses are relieved quickly, expansion and exfoliation are quick to follow... On the other hand, when pressure is released slowly by normal erosion, residual stresses can decay so gradually that only occasionally do they reach a differential capable of fracturing the rock".

Based on these and other arguments (p. 28, 33–34), it is believed that whatever the former rock load, removal of pressure by normal erosion is incapable of producing an appropriately rapid decompression of sufficient magnitude to result in large-scale sheeting. Sheeting structures seem to represent characteristic patterns indicating rapid decompression of a considerable order; with slow decompression effected by normal erosion the gradual decay of residual stresses will most probably be manifested in a small-scale exfoliation (p. 34) or in the opening of pre-existing latent joint directions of tectonic or other origin and these circumstances will give rise to unfavourable conditions for the development of sheeting structures (p. 20); see below under point vi).

On the other hand, the present hypothesis, which will be elucidated below by taking the development of large-scale sheeting on Sermersôq as an example, is not dependent on former rock loads and rate of erosion.

v) The comparatively recent (p. 15–16) large-scale sheeting on Sermersôq has originated at the end of the second glacial stage. Before the late-Cretaceous to early-Tertiary uplifts of the high-level erosion surface or pre-glacial peneplane (Chapter II; Oen in press) Sermersôq was part of a flat land. At that time the exposed rocks on Sermersôq may have shown jointing of the normal type, but large-scale sheeting structures had apparently not developed (p. 20–21). The higher near-surface parts of the post-tectonic batholiths and their immediately adjoining or overlying country rocks were constantly under the influence of the upward directed gravitational body forces arising from the mass deficiency of the batholiths. The vertical compression resulting from these forces may have prohibited the opening of any significant joint systems in the rocks affected, except in their exposed uppermost few meters. The upward directed forces and the vertical compression were greatly augmented when the late-Cretaceous to early-Tertiary differential uplifts of the old peneplane set in. Since large parts of this peneplane are still preserved at present as a high-level erosion surface, the rate of uplift must have been several times greater than the rate of erosion; as argued elsewhere (Oen, in press) these rapid uplifts seem to have been essentially completed or to have slackened down significantly at the end of the first glacial stage. At that time regional uplift and/or the epeirogenic doming of the granites had reached a certain value and then slackened down sufficiently or ceased entirely to cause an appropriate relative decompression of the rocks affected. It should be noted that owing to the combined effects of gravitational and epeirogenic forces the vertically upward directed forces were greater in the areas of post-tectonic granites than in their country rocks; during the period of differential uplifts these areas, lighter in weight, may have been risen more rapidly and for a greater amount than adjoining areas, so that the subsequent decompression will also be relatively greater and more rapid in areas where post-tectonic granites are exposed. Such circumstances together with the unjointed nature of the granites (see above and below under point 8) may account for the preferential development of large-scale sheeting in post-tectonic granite massifs.

As remarked by Kieslinger (1958, p. 99) it is not to be expected that sheeting of rock masses will occur immediately after the decompression, but rather that a time interval of geologic order may elapse between the decompression and the sheeting due to the relaxation of the stresses stored up in the rock mass. Thus, it is conceivable that a decompression as described above occurred on Sermersôq at the end of the first glacial stage, whereas the spontaneous large-scale sheeting in the exposed granites and adjoining rocks did not occur before the end of the second glacial stage. Sheeting due to dilatation or expansion after decompression can only occur in the upper rock layers near and at the surface; the direction normal to this surface is the only direction in which expansion of the rock mass is not hemmed by adjoining rock masses and, therefore, the sheeting structures will develop parallel to the topography existing at the time of sheeting.

With the present hypothesis the author believes to have accounted satisfactorily for:

a) the preferential development of large-scale sheeting in post-tectonic granites and associated rocks (p. 26),

b) the occurrence of sheeting structures at a niveau not appreciably below the former surface of an old, but recently uplifted peneplane (p. 16), and

c) the fact that sheeting seems to have occurred spontaneously within a geologically speaking very short time interval and shortly after the cessation of recent regional uplifts (p. 16).

It does not seem that large-scale sheeting, as distinct from small-scale exfoliation, is a continuous process keeping pace with the rate of erosion as might be expected if unloading by erosion is considered as the main cause of sheeting. Both points b) and c) suggest that large-scale sheeting on Sermersôq was not preceded by significant erosion of overlying rocks. The author cannot see how the above-mentioned relations can be satisfactorily explained by the current "load pressures and relief of load by erosion" hypothesis.

vi) The present hypothesis considers large-scale sheeting as a major response to an important and rapid decompression, releasing most of the stresses accumulated in the rocks over long periods of compression. After large-scale sheeting has occurred once, the residual stresses remaining in the rocks are strongly reduced and further sheeting can in general not occur unless new rapid decompressions take place. In many regions the large-scale sheeting of mountains is followed by a small-scale exfoliation of joint blocks and small exposures (p. 24). This indicates that after the large-scale sheeting is over, the comparatively small residual stresses left behind are in general sufficient to cause further exfoliation on a smaller scale and at later times. The frequently observed spontaneous fracturing of rocks in fresh quarries and tunnels often betrays the presence of such final residual stresses in already jointed or sheeted rocks. Measurement of natural stresses in tunnels and other underground workings in granite show that these stresses are higher than can be accounted for by the weight of overlying rock alone (Olsen 1957, Moye 1959). If these final residual stresses are released quickly, a small-scale exfoliation may ensue. Because these final stresses must be lower than the original stresses, the decompressions involved in their relaxation will also be of correspondingly smaller magnitude compared with the decompression required to initiate large-scale sheeting. Therefore, factors which are insignificant or of secondary importance in large-scale sheeting may become important in effecting the additional small decompressions necessary to initiate widespread superficial exfoliation on a small scale; such factors are e.g., the removal of superincumbent load by erosion, insolation, weathering, climate, etc.

In general, exfoliation becomes possible as soon as the amount of confining pressure removed by erosion exceeds a value which is dependent on the amount of unreleased stresses in the rocks. Since in exposed rocks the residual stresses are generally less than at some depth, the removal of confining pressures by rapid erosion may give rise to favourable conditions for a small-scale exfoliation at the surface or for the development of other types of jointing, before any large-scale sheeting by unloading can occur. In fact, a small-scale exfoliation keeping pace with the rate of erosion may result in a gradual decay of the originally much higher stresses in a mountain mass, preventing in this way the occurrence of large-scale sheeting. In other words, a given rate of erosion may be rapid enough to account for the small decompressions related with small-scale exfoliation at the surface, but it may fail to achieve a sufficiently quick relief of much higher pressures of the order involved in large-scale sheeting.

Large-scale sheeting and small-scale exfoliation in granites are phenomena which should be differently interpreted according to the different orders of mass, energy and time involved (LIVINGSTON 1956), but they are related by a common cause, and hence commonly associated. The primary cause of all sheeting and exfoliation is dilatation subsequent to decompression of rock masses containing considerable amounts of residual stresses, hence all the features consistent with GILBERT's hypothesis (p. 28) are equally so with the present hypothesis. The stresses were accumulated during previous periods of compression by upward directed gravitational body forces of deficient granite masses. During active epeirogeny the temporarily strongly augmented upward forces have a selective effect on the isostatically lighter granite areas, which react most rapidly by uplift tending to reduce the gravitational and epeirogenic forces. Large-scale sheeting is an initial major response to this decompression; afterwards any further sheeting or exfoliation is slight or on a minor scale, and probably governed by factors of secondary importance in large-scale sheeting as, e.g., the removal of rock loads by rapid erosion. However, it is realized that in particular instances of exfoliation on an intermediate scale it may be difficult not to over- or understate the role played by rock loads and rapid erosion.

vii) The absence of large-scale sheeting in basic igneous rocks, which nevertheless frequently show small-scale exfoliation of boulders and hill slopes, is entirely compatible with the present hypothesis. Large-scale deep sheeting, if genetically connected with gravitational forces caused by mass deficiencies in the upper crust, should not occur associated with massifs of basic rocks. However, the latter rocks apparently have mechanical and compositional properties which render them suitable to exfoliate easily, even when not attended by as significant a previous compression and later decompression as in the case of granite massifs. For these reasons the influence of secondary factors of exfoliation may appear so much more manifest in basic rocks that decompression by relief of load may suffice to initiate a widespread small-scale exfoliation,

e. g. in the case of the spheroidal exfoliation of joint blocks of certain basic dykes which are commonly observed in areas where no exfoliation phenomena occurs in the surrounding country rocks.

The exfoliation of massive sandstones as described by BRADLEY (1963) may represent an example of exfoliation on an intermediate scale, which is also mainly governed by the combination of suitable mechanical properties of the rock and factors of secondary importance in large-scale sheeting.

viii) The usual absence of sheeting in syntectonic granite massifs can also be understood. Syntectonic granites usually have greater lateral extensions and they are in general not characterized by vertical boundaries and significant negative gravity anomalies (BOTT 1956, p. 46). See further below under point x.

ix) Sheeting and exfoliation, which are generally absent in gneisses, do nevertheless occur in gneisses and other rocks in areas where large granite massifs are also present. This is consistent with the present hypothesis because the compressive stresses resulting from the gravitational and epeirogenic forces and the decompression after uplift will not only affect the granite, but also the overlying and immediately adjoining country rocks.

x) One of BOTT's (1953, 1956) main conclusions is that the gravity evidence is apparently in complete harmony with an emplacement of post-tectonic granites by a mechanism of magmatic stoping. The emplacement of the sheeted post-tectonic granites of N Portugal by a process of major stoping has been advocated by the author (OEN 1960), while the unpublished results of his work on Sermersôq support a similar mode of emplacement for the "new granite". Some special relation between sheeting and post-tectonic granites emplaced by magmatic stoping may thus be suggested, but further evidence is difficult to assess as granite emplacement and sheeting have not been considered from a common viewpoint by most geologists. Nevertheless, theoretical considerations based on the fact that a good sheeting develops only in rocks which are poor in or devoid of pre-existing joints (p. 20–21) suggest that granites emplaced by a stoping mechanism may be prone to develop a better sheeting than other granites. Syntectonic granites and those post-tectonic granites which have been forcefully injected in a partially crystallized state, usually have several systems of joints imposed by tectonic forces or the intrusive forces of the magma. With subsequent erosion these joints may conceivably open before effective decompression can cause sheeting. On the other hand, post-tectonic granites emplaced in the upper crust by stoping must have intruded in such a fluid state that joint directions cannot be imposed before the post-emplacement consolidation has set in. Furthermore, stoping is generally facilitated when the crust is under tension (OEN 1960) and after the emplacement of post-tectonic granites tectonic forces are usually not very important, while the compression exerted by the mass deficiency of the granites themselves may be an important factor in prohibiting the actual opening of joint systems during the subsequent history of the granite.

Thus, of all granites, those emplaced by magmatic stoping seem to have most chance to remain free of open joints until sheeting can occur. However, it should be stressed that the suggestion that granites emplaced by stoping may be prone to develop a better sheeting than other granites implies neither that all sheeted granites must have been emplaced by stoping, nor that all granites emplaced by stoping should show a good sheeting.

## 3. Conclusions.

A study of sheeting on the island of Sermersôq and a general inquiry into the causes and origin of sheeting have led to the conclusion that sheeting structures are caused by the dilatation of rock masses in a direction normal to the topography and subsequent to release of pressures. However, current views attributing compressive stresses only to rock load and the release of pressures to removal of overload by erosion are inadequate to explain all aspects of the problem. The intimate association in space of sheeting with exfoliated boulders and woolsacks, and with post-tectonic granite massifs indicates that the latter massifs must have some inherent property which originated widespread exfoliation phenomena. It is suggested that due to the mass deficiency represented by granite massifs of lower density than the surrounding rocks, gravitational body forces originate which tend to raise the deficient masses above their surroundings. In this way a vertical compression is exerted on the higher levels of the granite and surrounding country rocks. During periods of regional uplift the vertical stresses are temporarily strongly augmented by epeirogenic forces, but actual elevation of the region and contemporaneous updoming of the granites tend to compensate the existing anomalies and to reduce the gravitational forces. Thus, when regional uplift slackens down or ceases, a relative decompression of the combined gravitational and epeirogenic forces occurs rapidly, and favourable conditions for the spontaneous development large-scale sheeting in the near-surface rocks are realized. Removal of superincumbent load, insolation, weathering, climate, textural and compositional properties of rocks, are secondary factors capable of significantly enhancing exfoliation on a small or intermediate scale.

# REFERENCES


Adams, F. D. (1910), An experimental investigation into the action of differential pressure on certain materials and rocks, employing the process suggested by Professor Kick. Journ. Geol., Vol. 18, 489–525.

Adrian, F. von (1863), Beiträge zur Geologie des Kaurimer und Taborer Kreises in Böhmen. K. K. Geol. Reichsanst. Wien, Vol. 13, 155–182.

Axelrod, D. T. (1962), Post-Pliocene uplift of the Sierra Nevada, California. Bull. Geol. Soc. America, Vol. 73, 183–198.

Bain, G. W. (1931), Spontaneous rock expansion. Journ. Geol., Vol. 34, 715–735.

— (1938), Spontaneous rock expansion. Bull. Geol. Soc. America, Vol. 49, 1864.

Balk, R. (1937), Structural behavior of igneous rocks. Geol. Soc. America, Mem. 5, 177 pp.

— (1939), Disintegration of glaciated cliffs. Journ. Geomorphology, Vol. 2, 305–334.

Barbeau, J. & Geze, B. (1957), Les coupoles granitiques et rhyolitiques de la région de Fort-Lamy (Tschad). Bull. Soc. Géol. France, 6e Sér., Vol. 7, 341–351.

Barton, D. (1916), Notes on the disintegration of granite in Egypt. Journ. Geol., Vol. 24, 382–393.

— (1938), The disintegration and exfoliation of granite in Egypt. Journ. Geol., Vol. 46, 109–111.

Billings, M. P. (1942), Structural geology. Prentice-Hall, New York, 473 pp.

Blackwelder, E. (1925), Exfoliation as a phase of rock weathering. Journ. Geol., Vol. 33, 793–806.

— (1927), Fire as an agent in rock weathering. Journ. Geol., Vol. 35, 134–140.

— (1933), The insolation hypothesis of rock weathering. American Journ. Science, Vol. 26, 97–113.

Bott, M. H. P. (1953), Negative gravity anomalies over acid "intrusions" and their relation to the structure of the earth's crust. Geol. Mag., Vol. 90, 257–267.

— (1956), A geophysical study of the granite problem. Quart. Journ. Geol. Soc. London, Vol. 112, 45–67.

Bradley, W. C. (1963), Large-scale exfoliation in massive sandstones of the Colorado Plateau. Bull. Geol. Soc. America, Vol. 74, 519–528.

Branner, J. C. (1896), Decomposition of rocks in Brazil. Bull. Geol. Soc. America, Vol. 7, 255–314.

Bridgman, P. W. (1938), Reflections on rupture. Journ. Appl. Physics, Vol. 9, 517–528.

Bridgwater, D. (1963), A review of the Sydprøven granite and other "New granites" of South Greenland. Med. Dansk Geol. For., Vol. 15, 167–182.

Bucher, W. H. (1933), The deformation of the earth's crust. Princeton Univ. Press, Princeton, 518 pp.

Chapman, C. A. (1958), Control of jointing by topography. Journ. Geol., Vol. 66, 552–558.

CHAPMAN, C. A. & RIOUX, R. L. (1958), Statistical study of topography, sheeting, and jointing in granite, Acadia National Park, Maine. American Journ. Science, Vol. 256, 111–127.

CHAPMAN, R. W. & GREENFIELD, M. A. (1949), Spheroidal weathering of igneous rocks. American Journ. Science, Vol. 247, 407–429.

CLOOS, H. (1925), Tektonische Behandlung magmatischer Erscheinungen, Teil I. Das Riesengebirge. Borntraeger, Berlin, 194 pp.

COTTON, C. A. (1952), Geomorphology, an introduction to the study of landforms. 6th ed., Whitecomb & Tombs Ltd, Wellington, 505 pp.

DALE, T. N. (1923), The commercial granites of New England. U.S. Geol. Surv. Bull. 738, 1–488.

DODGE, T. A. (1947), An example of exfoliation caused by chemical weathering. Journ. Geol., Vol. 55, 38–42.

EMERY, K. O. (1944), Brush fires and rock exfoliation. American Journ. Science, Vol. 242, 506–508.

ENGELN, O. D. VON (1942), Geomorphology. The MacMillan Co., New York, 655 pp.

FARMIN, R. (1937), Hypogene exfoliation in rock masses. Journ. Geol., Vol. 45, 625–635.

GARLAND, G. D. (1950), Interpretations of gravimetric and magmatic anomalies on traverses in the Canadian Shield in northern Ontario. Publ. Dominion Obs. Ottawa, Vol. 16, no. 1, 57 pp.

— (1953), Gravity measurements of the Maritime Provinces. Publ. Dominion Obs. Ottawa, Vol. 16, no. 7, 187–243.

GILBERT, G. K. (1904), Domes and dome structure of the High Sierra. Bull. Geol. Soc. America, Vol. 15, 29–36.

GRIGGS, D. T. (1936), The factor fatique in rock exfoliation. Journ. Geol., Vol. 44, 783–796.

HARLAND, W. B. (1957), Exfoliation joints and ice action. Journ. Glaciology, Vol. 3, 8–10.

HERMANN, O. (1899), Steinbruchindustrie und Steinbruchgeologie, Berlin.

HÖGBOM, I. (1921), On the geological importance of forest fires. Bull. Geol. Inst. Upsala, Vol. 15, 117–124.

JAHNS, R. H. (1943), Sheet structure in granites: its origin and use as a measure of glacial erosion in New England. Journ. Geol., Vol. 51, 71–98.

KIESLINGER, A. (1958), Restspannung und Entspannung im Gestein. Geologie und Bauwesen, Vol. 24, 95–112.

— (1960a), Gesteinsspannungen und ihre technische Auswirkungen. Zeitschr. Deutschen Geol. Ges., Vol. 112, 164–170.

— (1960b), Residual stress and relaxation in rocks. Rep. Intern. Geol. Congr., XXI Session, Norden 1960, Part XVIII, 270–276.

KING, L. (1948), A theory of Bornhardts. Geogr. Journ., Vol. 112, 83–87.

KLAER, W. (1956), Verwitterungsformen im Granit auf Korsika. Erg. heft Petermanns Geogr. Mitt., no. 261, 1–146.

LAUTENSACH, H. (1950), Granitische Abtragungsformen auf der Iberischen Halbinsel und in Korsika, ein Vergleich. Congr. Intern. Géogr., Lisbonne 1948, Vol. 2, 270–297.

LEWIS, W. V. (1954), Pressure release and glacial erosion. Journ. Glaciology, Vol. 2, 417–422.

LIVINGSTON, C. W. (1956), Fundamentals of rock failure. Quarterly, Colorado School of Mines, Vol. 51, no. 3, 1–11.

LJUNGNER, E. (1930), Spaltentektonik und Morphologie der Schwedischen Skagerrack-Küste. Bull. Geol. Inst. Upsala, Vol. 21, 1–478.

MATTHES, F. E. (1930), Geologic history of the Yosemite valley. U.S. Geol. Surv., Prof. paper 160, 1–137.

— (1937), Exfoliation of massive granite in the Sierra Nevada of California. Abstr. Proc. Geol. Soc. America for the year 1936, 342–343.

MEINECKE, F. (1957), Granitverwitterung, Entstehung und Alter der Granitklippen. Zeitschr. Deutschen Geol. Ges., Vol. 109, 483–498.

MERILL, G. P. (1906), Rocks, rock weathering, and soils. 2nd ed., New York.

MEUNIER, A. R. (1961), Contribution à l'étude géomorphologique du Nord-Est du Brésil. Bull. Soc. Géol. France, 7er Sér., Vol. 3, 492–500.

MILLER, W. J. (1911), Exfoliation domes in Warren County, New York. N.Y. State Museum Bull. 149, 187–194.

MOYE, D. G. (1959), Rock mechanics in the investigation and construction of T. 1 underground power station, Snowy Mountains, Australia. Engineering Geology Case Histories no. 3, 13. P. D. TRASK, 13–44, Geol. Soc. America.

OBST, E. (1923), Das Abflusslose Rumpfschollenland in nordöstlichen Deutsch-Ost-Afrika. Mitt. Geogr. Ges. Hamburg, Vol. 35.

OELSNER, O. (1952), Die pegmatitisch-pneumatolytischen Lagerstätten des Erzgebirges mit Ausnahme der Kontaktlagerstätten. Die Bergakademie, Freiberger Forsch, h. 9, C 4, 5–80.

OEN, I. S. (1958), The geology, petrology and ore deposits of the Viseu region, northern Portugal. Comun. Serv. Geol. Portugal, Vol. 41, 1–199.

— (1960), The intrusion mechanism of the late-Hercynian post-tectonic granite plutons of northern Portugal. Geologie en Mijnbouw, Vol. 39, 257–296.

— (in press), Geomorphological observations on Sermersôq; a contribution to the geomorphology of South Greenland. Medd. Grønland.

OLSEN, O. J. (1957), Measurements of residual stress by the strain relief method. Quarterly, Colorado School of Mines, Vol. 52, no. 3, 183–204.

OXAAL, J. (1916), Norsk granit. Norges Geol. Unders., no. 76.

PARKER, P. J. & McDOWELL, A. N. (1955), Model studies of salt-dome tectonics. Bull. American Ass. Petrol. Geol., Vol. 39, 2384–2470.

ROMBERG, F. & BARNES, V. E. (1944), Correlation of gravity observations with the geology of the Smoothing-iron granite mass, Llano County, Texas. Geophysics, Vol. 9, 79–93.

RONDEAU, A. (1958), Les "boules" du granite. Zeitschr. Geomorph., Vol. 2, 211–229.

RUXTON, B. R. & BERRY, L. (1961), Notes on facetted slopes, rock fans and domes on granite in the East-Central Sudan. American Journ. Science, Vol. 259, 194–205.

SCHATTNER, I. (1961), Weathering phenomena in the crystalline of the Sinai in the light of current notions. Bull. Res. Counc. Israel, Sect. G, Vol. 10, 247–267.

SCHEIDEGGER, A. E. (1963), Principles of geodynamics. 2nd ed. Springer Verlag, Wien, 362 pp.

SHALER, N. S. (1869), Notes on the concentric structures of granitic rocks. Boston Soc. Nat. Hist., Proc., Vol. 12, 289–293.

SMITHSON, S. B. (1961), A regional gravity study over the Permian Baerum Cauldron of the Oslo region. Norsk Geol. Tidskr., Vol. 41, 211–222.

VOGT, J. H. L. (1879), Granitens og syenitens bænkning i forhold til den nuværende overflade. Geol. Fören. i Stockholm, Förh., Vol. 4, 439–446.

WARTH, H. (1895), The quarrying of granite in India. Nature, Vol. 51, 272.

WASHINGTON, H. S. (1922), Isostasy and rock density. Bull. Geol. Soc. America, Vol. 33, 375–410.

WATERS, R. S. (1952), Pseudo-bedding in the Dartmoor granite. Trans. Roy. Geol. Soc. Cornwall, Vol. 18, 456–462.

WEGMANN, C. E. (1938), Geological investigations in southern Greenland, Pt I. On the structural divisions of southern Greenland. Medd. Grønland, Vol. 113, no. 2, 1–148.

WHITNEY, J. D. (1865), Geology of the Sierra Nevada. Geol. Surv. of California, Geology, Vol. 1.

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