

LENNART SAMUELSSON

SELECTIVE WEATHERING OF
IGNEOUS ROCKS



STOCKHOLM 1973

SVERIGES GEOLOGISKA UNDERSÖKNING

SER C NR 690

ÅRSBOK 67 NR 9

LENNART SAMUELSSON

SELECTIVE WEATHERING OF
IGNEOUS ROCKS

STOCKHOLM 1973

ISBN 91-7158-031-X

STILNINGEN

STILNINGEN

C DAVIDSONS BOKTRYCKERI AB, VÄXJÖ 1973

CONTENTS

Abstract	3
Introduction	3
Description of weathered rocks	4
1. Permian dikes of the Swedish west coast	4
2. Doleritic sill on the east coast of northern Sweden	5
3. Granite gneiss of the Göteborg region	9
4. Granites in Saudi Arabia	13
Summary	15
Acknowledgements	15

Abstract

Four examples of selective weathering are given, viz. a rhomb porphyry dike, a dolerite sill, a granite gneiss, and a granite. It is tentatively proposed that an early and moderate deformation of the parent rock is the primary cause of the weathering.

Introduction

In this paper are collected some observations concerning selective weathering of igneous rocks from different geological environments. The examples of the heterogeneous collection are connected by a few common properties. In all instances the weathering gives a residual soil in which the main part of the rock minerals can be found rather unaltered. The weathering is selective and consequently weathered and fresh parts of the same rock are found side by side. Finally, according to the author's interpretation, the primary causes of the selective weathering in the examples described have some features in common.

Description of weathered rocks

1. PERMIAN DIKES OF THE SWEDISH WEST COAST

The Permian dike rocks of western Sweden can be divided into three main groups viz. ultramafic rocks, dolerites, and rhomb porphyries. The geology of the dikes has been investigated by a. o. Ljungner (1927), Askund (1947), and Samuelsson (1971).

The rhomb porphyries compose the largest dikes, with a maximum width of c. 50 m and a length of several tens of kilometres. These dikes are frequently composite (Fig. 1) and sometimes weathered. The margins are doleritic (in the following abbreviated Dm) being developed symmetrically on both sides of the dike and enclosing a rhomb porphyry with 20–25 vol% rhomb-feldspar phenocrysts (abbreviated Rpm). In the central parts of the dike a rhomb porphyry usually occurs containing c. 30 vol% phenocrysts (abbreviated Rpc). The different rocks are rather homogeneous with Rpc being the most acid and Dm the least. The contacts between the different rocks indicate that the present distribution was caused by three intrusions starting with Dm and ending with Rpc. The successive intrusion occurred before the previous magma was completely chilled. Usually a fissure opened along the median plane of the existing dike allowing the subsequent intrusion. In a few instances it has been observed that Rpc occupies a separate dike close to the main dike. One of these examples is described in Fig. 1 and treated below.

It is of importance to note that weathering is not observed when Dm, Rpm, and Rpc have their proper places in the dike (Fig. 1 D, southern part), while the weathering is prominent in the central parts of Rpm, when Rpc occupies a separate dike (Fig. 1 D, northern part). No petrographic differences have been found between Rpm at the southern and northern parts of Fig. 1 D and are not to be expected according to the petrogenesis (Samuelsson 1971). Thus it seems obvious that the selective weathering of Rpm is dependent on the position of the Rpc intrusion.

In the northern part of the dike in Fig. 1 D factors seem to have operated, which influence the weathering of Rpm. Firstly, the fact that Rpc partly occurs in a separate dike and partly within Rpm implies that the stress-distribution during cooling of Rpm must have varied along the length of the dike. The opening of a new fissure parallel to the main dike must have caused a dynamic disturbance in Rpm. According to the relationships between the different dike-rocks, the Rpc intrusion occurred before Rpm was completely chilled. It is thus to be expected that this limited dynamic disturbance caused the partly established grain-boundaries in Rpm to break up. The boundaries might then have been penetrated and healed by late-magmatic solutions giving chlorite, ser-

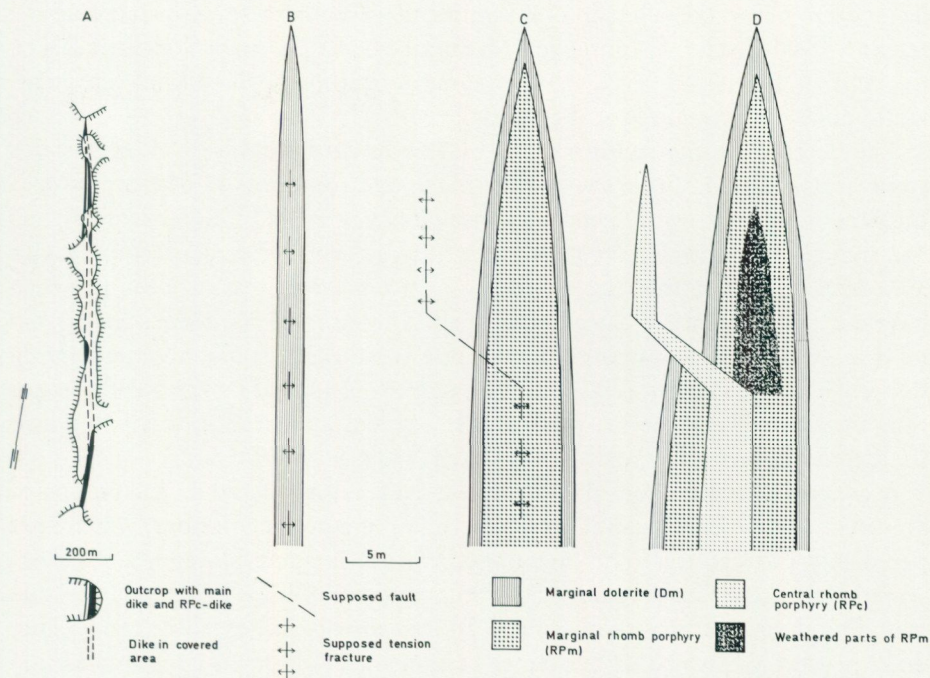


Fig. 1. Tentative interpretation of the composite intrusion at Skogen, 4.5 km NNE of Kungshamn church. A. Sketch-map of the dike, B to D - interpretation: B. Dolerite (Dm) is intruded. C. The first intrusion of rhomb porphyry (RPM) occurs and a new fracture is under development to the west of the main dike. D. After the second intrusion of rhomb porphyry (RPC).

pentine etc. These minerals are found in great abundance in a thin section from the weathered part of RPM.

Secondly, the occurrence of RPC in a dike separated from the main dike by a 3 m broad slice of granite requires that the RPC magma itself and its hot gases were hindered from contact with RPM. Both this magma itself and its thermal action can be expected to have had a "healing effect" on a tectonically disturbed RPM in dikes with the normal symmetrical rock distribution.

2. DOLERITIC SILL ON THE EAST COAST OF NORTHERN SWEDEN

The observations were made on Storön ($18^{\circ}13'E$, $62^{\circ}45'N$) in the parish of Nora, Västernorrland county. The geology of the area has been treated by Lundbohm (1899), Sobral (1913), and von Eckermann (1938). The present observations were made in connection with regional mapping by the Geological Survey of Sweden. A sketch of the general geology of Storön is given in Fig. 2.

The dolerite belongs to the post-Jotnian intrusions, which occupy large areas in the Västernorrland county, mostly as sills. Thicknesses of more than 200 m

have been observed. The dolerite frequently weathers to a coarse-grained regolith locally used as top-cover on minor roads. At many localities along the coast it can be observed that the dolerite has joints filled with late magmatic minerals a. o. albite and calcite.

The dolerite on the southern part of Storön conformably overlies a sandstone, dipping 5°SE. From the contact-plane and some tens of metres upwards the dolerite is split up into megacolumns (Spry 1962, p. 196) with diameters of 1 to 5 m. At c. 15 m above the base there is a rock surface conformable with the contact plane. In the vicinity of this surface megacolumns are found which have a weathered core and a resistant shell. There are all transitions from fresh to completely disintegrated columns. The weathering starts obviously from the center of the column (Fig. 3 B). The pattern produced by the weathering is thus the opposite to the more normal spheroidal appearance, this being also frequently met with in the dolerites of the Västernorrland county.

A genetic interpretation of the peculiar weathering of the megacolumns of Storön must take into account the action of late-magmatic solutions, which have percolated through the joints mentioned earlier. In some places it can be observed that these late-magmatic infillings of fissures have prevented the surrounding dolerite from weathering. This can also be observed at the locality described here. In some of the larger columns it is observed that, in addition to the joints which surround the column, there are joints going radially inwards, in some cases, crossing the center of the columns (Fig. 3 D). Penetration of these two types of joints by late-magmatic fluids have apparently inhibited the subsequent weathering of the dolerite at least for a few centimetres inwards from the fissures. The radiating joints have no effect, however, on the development of the concentric weathering of the columns. Thus, the primary cause of weathering pre-dates the local inhibition of the weathering related to radiating fissures. As the mineralisation of the latter seems to be synchronous with the mineralisation of the columnar joints, the latter mineralisation cannot have any effect on the primary cause of weathering.

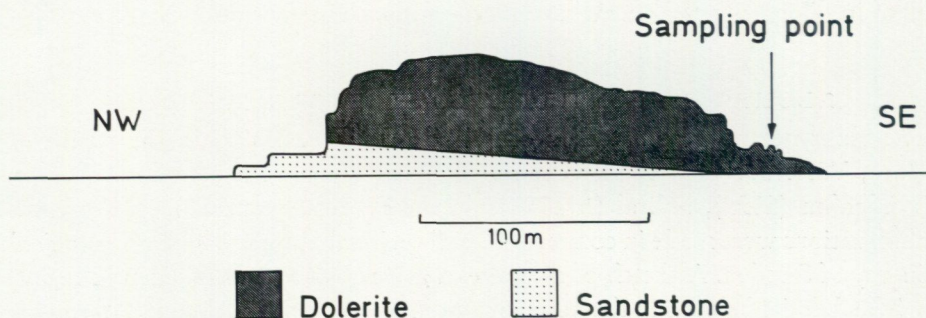


Fig. 2. Sketch profile of Storön, Nora, with sampling locality.

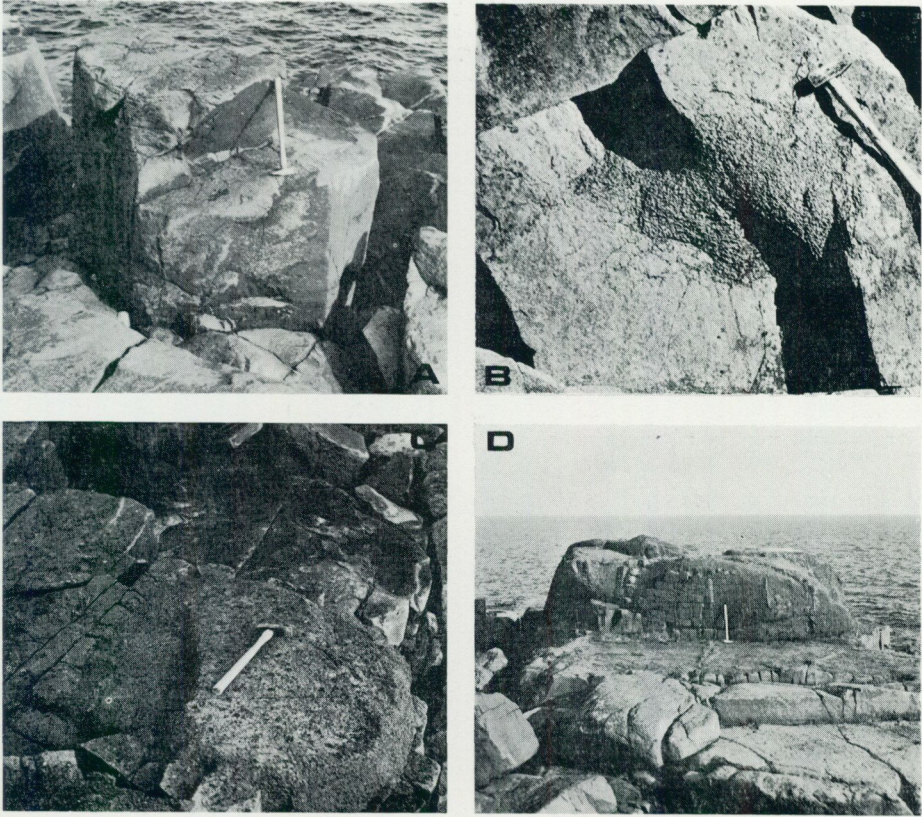


Fig. 3. Successive stages of weathering in megacolumns. A. Fresh megacolumn. B. Disintegration starts from the centre of a megacolumn and advances outwards along microfissures. C. Advanced stage of weathering. D. Completely disintegrated megacolumn with resistant rock close to the bordering fractures and along radiating fractures.

The column shown in Fig. 3 B has been investigated in three thin sections (Table 1). The minerals have only been studied by optical methods and the tables in Tröger (1959) have been used. No differences in the primary compositions of the minerals from the different samples have been observed. The plagioclase is zoned from An_{72} to An_{48} . The pyroxene is a ferroaugite with c. $(CaSiO_3)$ 35 %, $(MgSiO_3)$ 20 %, $(FeSiO_3)$ 45 %. The composition of the olivine is c. Fo_{60-65} . The biotite is pleochroitic in yellow-brown colours in all three samples. The overall high olivine content and its variation may indicate the cumulative character of this mineral (Lundqvist and Samuelsson, in preparation). The most prominent phenomenon shown by the three samples studied is an increased alteration of the olivine crystals towards the center of the column. Most of the serpentinized olivines are situated close to thin fissures,

Table 1. Mineral compositions of dolerite, Storön. Percentage by volume. Sample no. 1 is from the outer part of a megacolumn, no. 2 about 20 cm inside no. 1, and no. 3 about 30 cm inside no. 1 (1000 points counted per sample).

Minerals	Sample number		
	1	2	3
Plagioclase	53	55	53
Fresh olivine	24	16	19
Altered olivine	8	10	13
Pyroxene	8	12	9
Biotite	3	3	2
Opaque	4	4	4
Total	100	100	100

which are filled with chlorite (Fig. 4). The frequency of such fissures increases towards the center of the column (Fig. 3 B).

Thus, it is obvious that the weathering is related to the alteration of the olivine. It is also clear that this alteration has some connection with the development of the microfissures. Further, it is apparent that the formation of the microfissures, the alteration of the olivine, and subsequent related weathering were caused by processes acting within a discrete column, not crossing its borders.

Interpretation of the genesis of the weathering is influenced by evidence for the temperature at which the joints may have formed. Spry (1962, p. 214) gives some notes concerning the temperature of jointing in basalts: "Although it is not possible to be sure, the evidence suggests that some joints may have formed at temperatures as high as 900°C., many have formed by the time the temperatures has fallen to 800°C. and possibly most jointing is complete by 700°C." Macdonald (1967, p. 40) describes the dramatic opening of fissures in a 6 m thick crust covering a pool of lava. Thus it is clear that thermal jointing is possible in connection with only partly crystallized lava flows.

On Storön, in the vicinity of the lower contact, the megacolumns developed from below upwards towards the centre of the sill, probably simultaneously with the crystallization. Spry (1962, p. 198) refers to some examples of basalt crystallization occurring later in the central parts of joint blocks than in their margins. Some parageneses indicate that the crystallization of the central parts was completed well below the temperature at which jointing might have started. Thus, on Storön, it was possible for a column, at a specific level for each moment in the cooling sequence, to have had a crystallized marginal part and a partly liquid central part. For adjacent columns the level mentioned should have been at the same distance from the sill contact, with some minor deviations according to the width of the columns.

This arrangement means that the central parts of the megacolumns, during cooling, have been in liquid contact with the volume of magma above. A momentary disturbance anywhere in the magma would thus affect the still liquid cores of the columns by hydraulic transmission. In this way the observed microfissures might have been formed. The disturbance could have been caused by faulting or by a new injection of magma. Evidences of tectonic disturbances of the crystallizing magma have been observed by Fil. kand. S.-Å. Larson, University of Gothenburg, during his study of these dolerites (personal communication). Indications of a second intrusion have been observed by Lundqvist and Samuelsson (in preparation).

It is obvious that the alteration of the olivine is essential for the later weathering of the rock. This alteration and its localisation to the cores of the columns might have been caused by the trapping of gases in the latest crystallizing parts of the columns (cf. Spry 1962, p. 214). However, this should be a continuous process, not restricted to a specific level above the sill contact, as is the case on Storön. It is also difficult to explain the occurrence of microfissures by this process.

3. GRANITE GNEISS OF THE GÖTEBORG REGION

The occurrence of weathered rock near Göteborg can be read from maps by Sandegren and Johansson (1931) and Lundegårdh (1953, 1958). The rock is medium to coarse grained, granitic, and normally schistose. In some cases it

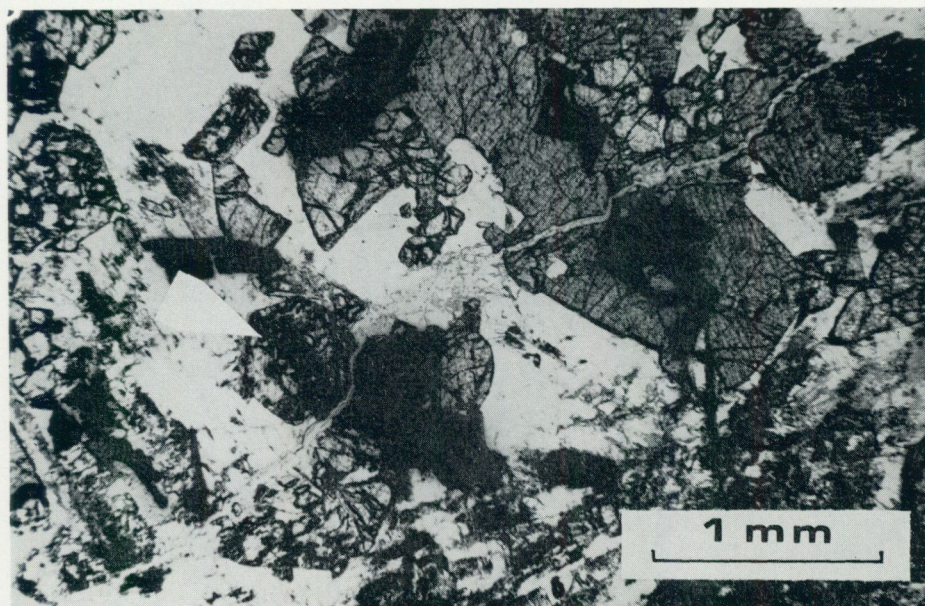


Fig. 4. Microfissure with chlorite. The arrow points at serpentinized olivine. 1 Nic.



Fig. 5. Residual soil of disintegrated granite gneiss. Unweathered rock below the hammer. W. Blixås, S. Mölndal.

disintegrates to a gravel regolith (Fig. 5) where structures such as foliation, pegmatitic veins etc. are found undisturbed. Since the deglaciation, c. 12 000 BP, a 3–4 m thick regolith has developed at some places. This implies an average disintegration rate of 0.3 mm/year. Sandegren and Johansson (1931, p. 34) noted that the weathering is pronounced in the most even-grained and alkaline parts of the rock. Lundegårdh (1958, p. 45) refers to a thermo-chemical investigation by P. Ljunggren, which showed that the weathering is mechanical in character.

The material to the present investigation has been collected from the area south of Göteborg. The petrographical and structural variations of the rock, which can be observed in the field, have obviously no direct influence on the localisation of the weathering. To see if there are any microscopically visible characteristics, influencing weathering, thin sections have been studied from

Table 2. Mineral compositions of granite gneiss, Mölndal, S. Göteborg. Percentage by volume. (1000 points counted per sample).

Minerals	Sample numbers							
	I	II	III	IV	V	VI	VII	VIII
Quartz	46.7	29.4	37.2	27.7	35.0	35.3	33.8	29.1
Microcline	30.0	39.1	35.3	44.7	30.7	33.0	39.4	37.1
Plagioclase	13.2	23.7	21.6	21.3	24.5	22.6	18.0	26.7
Biotite	5.3	5.5	1.4	3.0	5.7	4.0	3.9	2.2
Amphibole	+	-	+	-	-	+	-	-
Pyroxene	-	-	1.5	-	-	2.0	-	-
Opaque	1.7	0.7	2.0	2.3	0.7	0.6	2.1	0.5
Sphene	1.9	0.1	0.3	0.3	1.3	0.7	0.2	0.5
Apatite	0.3	+	+	+	+	0.2	+	+
Zircon	0.2	+	0.2	0.2	0.2	+	0.1	+
Fluorite	0.4	0.8	0.3	0.5	0.6	0.4	0.1	0.1
Montmorillonite in grain boundaries	0.1	0.8	0.2	0.1	1.3	1.2	2.5	3.8

Sample nos. I-IV are from macroscopically fresh rock, without weathering in the surroundings.

V-VIII are from macroscopically fresh rock, beneath residual soil.

- I Quarry, Bunketorp, S. Mölndal.
- II Quarry, N. Blixås, S. Mölndal.
- III Fklanda, W. Mölndal.
- IV 80 m below bedrock surface, drill-core. Bunketorp, S. Mölndal.
- V W. Blixås, S. Mölndal.
- VI Eklanda, W. Mölndal.
- VII Bunketorp, S. Mölndal.
- VIII 21 m below bedrock surface, drill-core. Bunketorp, S. Mölndal.

- a) macroscopically fresh rock without any weathering in the surroundings,
- b) macroscopically fresh rock beneath residual soil.

The mineralogical composition and its variation is given in Table 2. Samples nos. I, II, IV, V, VII and VIII are from the area south of the valley between Mölndal and Askim, nos. III and VI from the northern slopes of the valley. Alkali-pyroxene is found only in the latter samples. It is accompanied by an alkali-amphibole.

The mineralogical differences between the samples have obviously no influence on the capacity for weathering, except for the occurrence of montmorillonite. This mineral is found as a thin film around the mineral grains and occasionally in the cleavage planes of the feldspar (Fig. 6). The montmorillonite has been identified by X-ray diffraction at the laboratories of the Geological Survey of Sweden. Although this mineral is found in all samples, it influences the weathering only when the grain-boundary film makes a continuous network through the rock. The montmorillonite is younger than all other minerals as well as the schistosity of the rock.

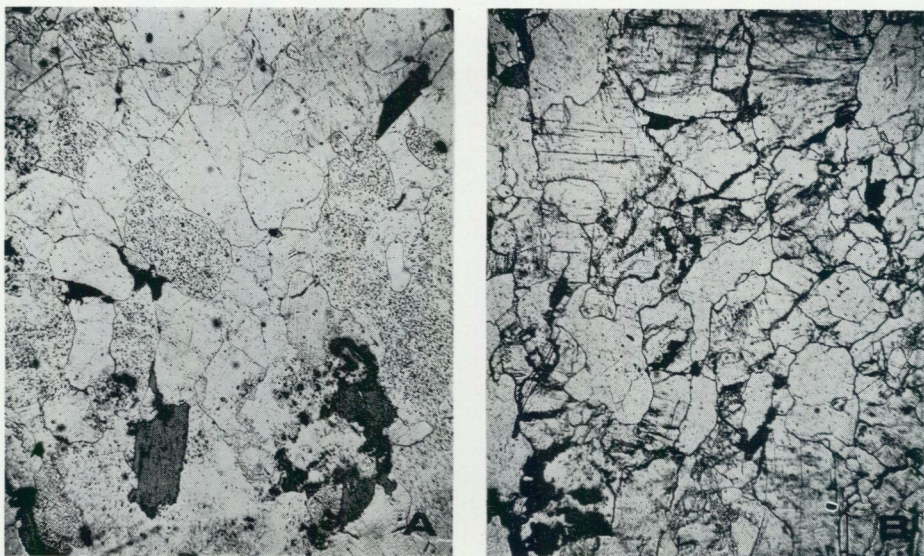


Fig. 6. Granitic gneiss, S. Göteborg. 15 \times , 1 Nic.
 A. Fresh rock. Sample no. IV, Table 2.
 B. Macroscopically fresh rock beneath residual soil.
 Sample no. VIII, Table 2.

There is obviously a positive correlation between the present distribution of weathered rock and the clay mineralisation mentioned above. The montmorillonite mineralisation and the deformation, which opened the grain boundaries, have most probably been synchronous. From the geological maps (Lundegårdh 1953, 1958) it is seen that the elongation of the weathered areas is parallel to the general schistosity. This has also been verified by diamond-drilling, whereby a 0.5 m broad zone of weathering was refound at a depth of 20 m and lying within the schistosity. The schistosity has to some extent guided the later deformation and clay mineralisation.

In some cases it is possible to follow the weathered rock towards and into the prominent schistosity and fault zone at Källered (cf. Lundegårdh 1953, 1958). Towards the centre of the zone, the rock becomes more and more crushed, culminating in exposures of mylonite in the bottom of the valley. No weathering has been observed in the more or less mylonitized rock and no clay mineral can be observed in the slides. However, there are some scattered small occurrences of chlorite throughout the rock. This mineral is also found on the slip surfaces. Clay minerals are restricted to narrow zones.

Moderate deformation of the granite gneiss appears to have been a prerequisite for the weathering. The fact that the chemistry of the rock is not suitable for the formation of montmorillonite, taken along with the strict limitation of the clay mineral to grain boundaries and clear-cutting mineral

fissures, makes it necessary to postulate an external source for most of the clay-forming material. As the network of the clay-film is found unchanged to considerable depths (> 20 m) in the rock and as the conditions for development of vaste volumes of homogeneously but only slightly deformed rock are not to be met with close to a land surface, the clay mineralisation probably has been caused by endogenic processes (hydrothermal).

In view of the considerably large volumes of weathered rock and the extensive area where the scattered occurrences are found (Lundegårdh 1953, 1958), the endogenic processes must be ascribed to a metamorphism of regional extension. Unmetamorphosed Cambrian breccias have been recorded from basement fissures in the Göteborg area (Samuelsson 1967, Martinsson 1968). Thus pre-Cambrian orogenesis was probably responsible for the metamorphism. The youngest pre-Cambrian orogeny was the Dalslandian. The effect of this orogeny on the rocks of the Göteborg region has previously been discussed by Lundegårdh (1953, 1958) and it seems reasonable to ascribe the tectonisation and clay mineralisation to some phase of this period of regional metamorphism. A pegmatite at Högsbo, Göteborg, has been dated to c. 930 million years, which represents a late stage in the Dalslandian orogeny (Welin and Blomqvist, 1964).

Since the clay mineralisation has an external source it might be expected that the same kind of weathering would occur in other rocks of the region and to the same extent. This is not the case. There are a lot of granodiorites and quartz-diorites in the area. Important differences between these rocks and the weathered rock are the lower contents of micas and amphiboles and higher content of microcline of the latter. The higher content of micas and amphiboles is probably responsible for the properties of elasticity, which prevented suitable deformation of the intermediate rocks. It should also be observed that the occurrences of weathered rock are found at a rather constant distance parallel to the contact of the granite gneiss. It seems probable that the mineralogical factor and the location factor have cooperated in the development of the moderate deformation, which is the ultimate cause of the selective weathering in the Göteborg area.

4. GRANITES IN SAUDI ARABIA

The strong mechanical weathering common in arid areas is usually ascribed to the temperature differences between day and night. Without entering into discussion of this general process, I would like to describe how different parts of a granite give a varied response to identical weathering agencies.

The observations are from the area c. 20 km to the south of Mecca. The rocks have only been investigated in the field. A granite intrusion has been studied in a more or less circular batholit, c. 10 km in diameter. The initial magma gave a porphyritic granite, which now occupies the outer parts of the

body. Subsequent crystallization produced an even-grained biotite-granite. The latest rocks to crystallize were pegmatite, aplite, and aplitic granite. The contact between the porphyritic and the even-grained granite is in part gradational, in part sharp, the even-grained granite being the younger. The pegmatite, the aplite, and the aplitic granite have intrusion contacts with the other granites.

The different rocks are interpreted as parts of the same parent magma. Thus there have been movements within the magma chamber after the crystallization of the porphyritic granite. The latter has a foliated structure and is more rapidly weathering than the other rocks. At one locality it has been observed that the aplitic granite has intruded between the porphyritic granite and its wall rock (Fig. 7). Xenoliths of porphyritic granite are found in the aplitic granite. The latter is, as usual, rather resistant to the weathering while the xenoliths and the porphyritic granite of the wall-rock are strongly weathered.

The succession of increasing weathering is: A, pegmatite, aplite, and aplitic granite, B, even-grained granite, C, porphyritic granite. There are both mineralogical and structural differences between the different rocks. They have not been studied in any detail and it is thus impossible to make any definite state-

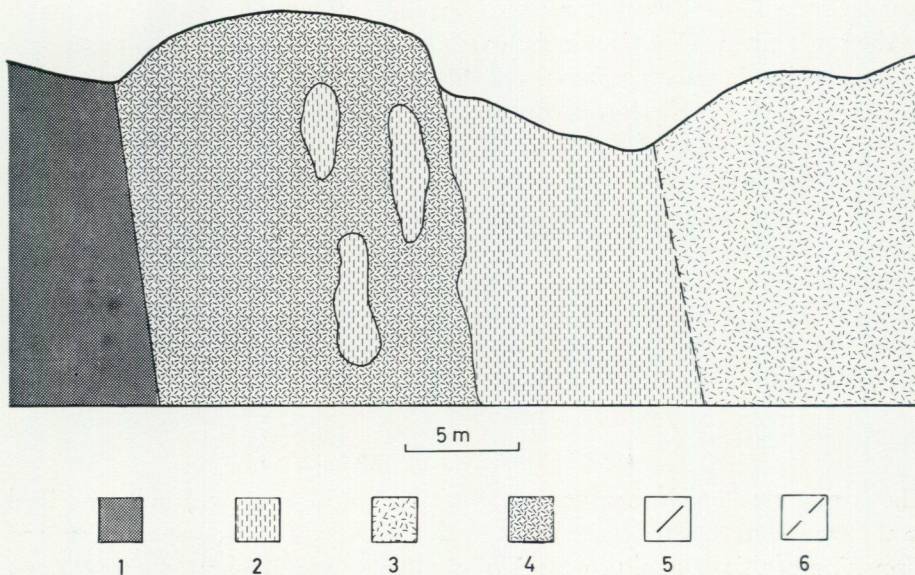


Fig. 7. Sketch-profile from an area south of Mecca, Saudi Arabia.

1. Diorite.
2. Foliated porphyritic granite.
3. Even-grained granite.
4. Aplitic granite.
5. Sharp boundary.
6. Transitional boundary.

ment about the primary cause of the selective weathering. It is tentatively proposed, however, that the foliation of the porphyritic granite was caused by a mechanical disturbance, which interrupted the establishment of the grain boundaries. This facilitated the present mechanical disintegration of the porphyritic granite.

Summary

In accordance with the tentative interpretation proposed for each examples of weathering, the primary cause of the selective weathering can be ascribed to some kind of mechanical disturbance. This occurred in connection with the crystallization of the rocks in the examples 1, 2, and 4. The deformation of the rock in the example number 3 occurred at a later metamorphic episode.

A consequence a. o. of this kind of early formed disposition for weathering is that even in recently deglaciated areas, e. g. Scandinavia, a considerable regolith (in the Göteborg region more than 3 m deep) might have had time to develop. It should also be possible for post-glacial weathering to develop beneath a cover of till. It is thus necessary to consider the primary cause of the weathering before a deeply disintegrated rock is attributed to pre-glacial weathering (cf. discussion by Hillefors 1969, p. 21 and Mattsson 1962).

Acknowledgements

Centre for Applied Geology, Jeddah, Department of Geology, Chalmers University of Technology, Göteborg, Geological Survey of Sweden, and Kjessler & Mannerstråle AB, Göteborg, have in different ways contributed to this paper. The English language has been revised by Dr. David Gee, Geological Survey of Sweden. To all I express my sincere gratitude.

REFERENCES

- GFF – Geologiska Föreningens i Stockholm Förhandlingar
 SGU – Sveriges geologiska undersökning, Stockholm
- ASKLUND, B., 1947: Svenska stenindustriområden. I–II. Gatsten och Kantsten. SGU C 479.
- VON ECKERMANN, H., 1938: The Anorthosite and Kenningite of the Nordingrå–Rödö Region. A Contribution to the Problem of the Anorthosites. GFF 60, pp. 243–284.
- HILLEFORS, Å., 1969: Västsveriges glaciala historia och morfologi. Medd. Lunds Geografiska Inst., Avh. 60.
- LJUNGNER, E., 1927: Spaltentektonik och Morphologie der schwedischen Skagerrakküste. I–II. Bull. Geol. Inst. Uppsala. Vol. XXI. Uppsala.
- LUNDBOHM, HJ., 1899: Berggrunden inom Vesternorrlands län. SGU C 177.
- LUNDEGÄRDH, P. H., 1953: Petrology of the Mölndal–Styrsö–Vallda region in the vicinity of Gothenburg. SGU C 531.
- 1958: Göteborgstraktens berggrund. SGU C 553.
- LUNDQVIST, TH. and SAMUELSSON, L., in preparation: The differentiation of a dolerite at Nordingrå, Central Sweden. SGU C 692.
- MACDONALD, G. A., 1967: Forms and Structures of Extrusive Basaltic Rocks. Basalt 1. New York.
- MARTINSSON, A., 1968: Cambrian paleontology of Fennoscandian basement fissures. Lethaia Vol. 1, pp. 137–155. Oslo.
- MATTSSON, Å., 1962: Morphologische Studien in Südschweden und Bornholm über die nicht-glaciale Formenwelt der Felsenskulptur. Lund Studies in Geography., Ser A no. 20.
- SAMUELSSON, L., 1967: Breccia av paleozoiska bergarter 1,5 km väster om Bohus fästning, Kungälv. GFF 89, pp. 484–459.
- 1971: The relationship between Permian dikes of dolerite and rhomb porphyry. SGU C 663.
- SANDEGREN, R. and JOHANSSON, H. E., 1931: Kartbladet Göteborg. SGU Aa 173.
- SOBRAL, J. M., 1913: Contribution to the Geology of the Nordingrå Region. Uppsala.
- SPRY, A., 1962: The origin of columnar jointing, particularly in basalt flows. Geol. Soc. Australia Jour. 8, pp. 191–216.
- TRÖGER, W. E., 1959: Optische Bestimmung der gesteinsbildenden Minerale. Teil I. Stuttgart.
- WELIN, E., and BLOMQVIST, G., 1964: Age measurements on radioactive minerals from Sweden. GFF 86, pp. 33–50.

PRISKLASS C

Distribution

SVENSKA REPRODUKTIONS AB

FAK, 162 10 VÄLLINGBY 1

Växjö 1973 C Davidsons Boktryckeri AB

Printed in Sweden

ISBN 91-7158-031-X