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3.1 Microclimate, Weathering Processes and Salt within Ice-free Continental Antarctica

By Franz-Dieter Miotke*

Summary: The conditions of weathered rock surfaces, the microclimate and salt concentrations in rocks and soils are essential for chemical weathering processes as well as for biological activities. Salt-enriched upper rock layers influence growing conditions for meirofaunas and floras and cause salt fretting, one of the major weathering processes in extremely dry and cold Antarctica. This paper summarizes field and labwork results about the microenvironment gained from three expeditions (1976—1981) to South Victoria Land, Antarctica.

Zusammenfassung: Die Bedingungen von verwitterten Gesteinsoberflächen, das Mikroklima und die Salzkonzentrationen in Gesteinen und Bodensubstraten sind für den Geomorphologen ebenso wichtig wie für Biologen, die in der kontinentalen Antarktis forschen.
Temperaturen über dem Gefrierpunkt und genügend Feuchtigkeit im Gestein und Boden sind notwendig für chemische Verwitterungsprozesse wie für biologische Aktivitäten. Salzangereicherte, obere Gesteinsschichten beeinflussen die Wachstumsbedingungen für die dortige Mikrofauna und -flora und verursachen Salzsprengung, einer der wichtigen Verwitterungsprozesse in der extrem trockenen und kalten Antarktis.
Diese Veröffentlichung faßt Feld- und Laborergebnisse über die Standortbedingungen im Mikroklima der zentralen Antarktis zusammen, die aus drei Forschungsreisen ins südliche Victoria-Land, Antarktis, (1976—1981) erzielt wurden.

1. FOREWORD

Exposure to sunshine and prevailing winds are essential factors to lichens growing on the surface of rocks. If a rock on a slope changes its position due to slopeforming processes or becomes overrun by loose debris, living conditions for lichens can deteriorate dramatically.

Our studies have shown that slope surfaces in the Dry Valleys — even of a low gradient — are not nearly as stabile as has often been assumed (MIOTKE 1984). Another field of geomorphology which I studied in Antarctica was that of aeolian activities, as, for example, wind polish and sand accumulation.

Lichens living on a pavement stone cannot survive, if sand and snow erosion become too severe or a sand cover too thick (MIOTKE 1982, 1982a, 1985).

On the other hand, geomorphologists interested in problems of weathering wonder what lichens do to the rock. To what extent do lichens weather the rock and also alter the microclimate of its very surface?

The interests and questions of biologists and geomorphologists overlap occasionally.

In this paper it will be dealt with own geomorphological results from three field seasons in Antarctica. It is not intended here to discuss the general literature on weathering processes in Antarctica (see MIOTKE 1982, MIOTKE & VON HODENBERG 1983) or to compile results archieved by microbiological or lichenological studies with respect to rock weathering (see FRIEDMANN 1982).

2. INTRODUCTION

Land forming takes place as a consequence of weathering. Weathering prepares solid rocks for erosion and transportation, which is why geomorphological studies have to start by investigating the weathering conditions in the area under study.

Very little basic data about the physical and chemical weathering processes in Antarctica was available when I started my geomorphological research in South Victoria Land in the mid-seventies. Therefore I had to set up my own measurement program.

* Prof. Dr. Franz-Dieter Miotke, Geographisches Institut der Universität Hannover, Schneiderberg 50, D-3000 Hannover, Federal Republic of Germany.

3. THE WEATHERING CONDITIONS AND PROCESSES

3.1 *The Importance of the Climate*

Besides petrographic properties, the climate has the strongest influence on the type and velocity of weathering. The rate of most chemical reactions increases with a rise in temperature and moisture content. Dominant weathering processes and, consequently, typical landforms will develop depending on the local macroclimate.

The Dry Valley region has an extremely cold and dry polar climate without rain and with an annual mean temperature of about — 20° C. The surfaces are almost completely free of visible vegetation.

However, this large-scale climatological picture is substantially modified by altitude, exposure to sun and prevailing winds as well as by distance from the milder and moister coastal areas. Hypsometric and peripheral-central alterations cause several different mesoclimates from the coast over the mountains to nunataks protruding from the inland ice.

The climatological setting suggest that chemical weathering is negligible and only physical rock disintegration can be expected to be of major importance. We shall see later that this does not hold true without reservation.

If we take a closer look at some weathering forms on a smaller scale, we cannot help noticing great differences. Even around a single boulder the degree of weathering can be quite diverse. Nearly unchanged rock surfaces can neighbor decomposed, salt-covered spots.

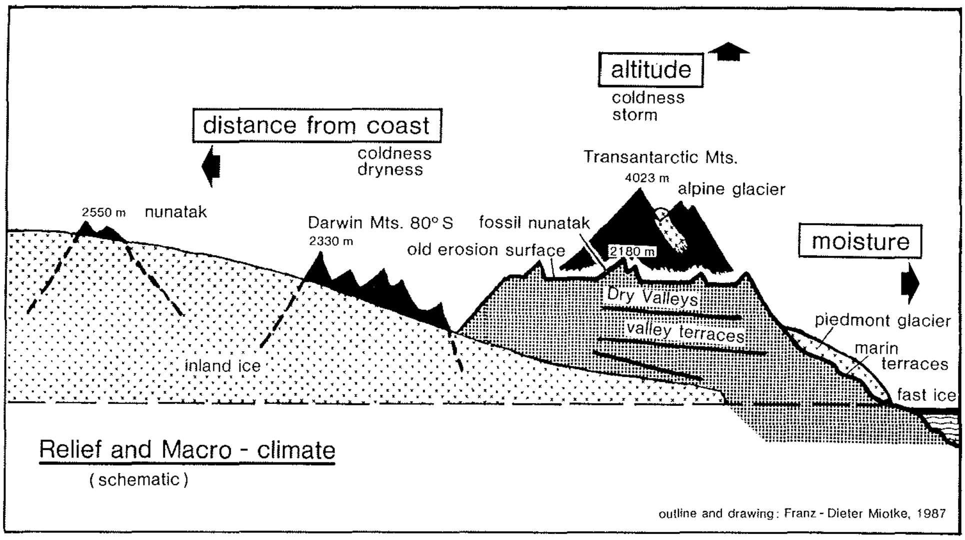


Fig. 1: While the humid marine air masses flowing onto the Transantarctic mountains considerably nourish the Piedmont Glacier, the Dry Valleys on the leeward side of the mountain range stay largely free of a permaent snow and ice cover. Especially nunataks protruding from the inland ice are exposed to a very harsh polar climate. The longer weathering takes places under such conditions, the more pronounced are the resulting forms (e. g., pseudotafoni) and the higher are the salt quantities accumulating, which weathered out and cannot be washed away due to lack of liquid water. Consequently, weathering forms on young valley floors, on higher valley terraces and on high up existing old erosion levels show a clearly different defeloping stage.

Abb. 1: Die Verwitterungsbedingugnen sind durch das extrem trockene und kalte Makroklima der kontinentalen Antarktis bestimmt. Reliefhöhe, Nähe oder Distanz von der relativ wärmeren und feuchteren Küste sowie reliefbdingte Expositionsunterschiede zur sommerlichen Sonneneinstrahlung und den vorherrschenden Winden schaffen jedoch graduell verschiedene Mikroklimate, die für die Verwitterung und die dort existierende Mikroflora und -fauna gravierend unterschiedliche Standortbedingungen erzeugen. Während die feuchten marinen Luftmassen, die auf das transantarktische Gebirge wandern, am Fuß des Gebirges noch mächtige Piedmont-Gletscher ernähren können, bleiben im Lee des Gebirges die Trockentäler weitgehend frei von einer permanenten Schnee- und Eisbedeckung. Die aus dem Eis herausragenden Nunatakker besitzen ein besonders extremes Polarklima. Je länger die Verwitterung unter gleichartigen Bedingungen dauert, umso ausgeprägter werden die Formen (Pseudotafoni!) und um so höher die ausgewitterten Salzgehalte, die mangels flüssigen Wassers nicht ausgewaschen werden können. Entsprechend sind die Verwitterungsformen in den jungen Talböden, den höheren Talterrassen und den hochliegenden alten Erosionsniveaus in ihrem Entwicklungszustand höchst unterschiedlich.

Obviously, the microenvironment close to the ground and rock surface is much more variable than the macroclimate reveals. Routine temperature measurements at 2 m above ground, for instance, are of no great use for informing us about the microclimate around and within rocks, which, however, we need to know in order to understand weathering processes in detail. In addition, we have to consider the daily, or rather minutely temperature changes because of their importance for determining how long higher temperatures permit certain processes to take place. The same considerations apply to the evaluation of the changing moisture content in rocks and soils.

In summary it can be said that the temperature differences in the microclimate are more extreme than in the overall macro- or mesoclimate. In the summer, the maximum and minimum temperatures of rock surfaces show a much wider daily range than the surrounding air temperatures.

During a clear summer day, the temperature climbs from –5° C all the way up to +29° C. When it is overcast, the temperature amplitude is less than 10° C. In 40 cm depth, nearly no daily alteration is noticed. These temperatures were measured directly behind a dolorite plate approximately 2 cm thick. In white marble maximum temperatures only reached +10° C. Different rock types showed differences due to colour and petrography. (MIOTKE 1982) Much of such basic information we collected for geomorphological purposes, but data on temperature, moisture, salt concentration, minerals and rock properties are of interest for biologists as well.

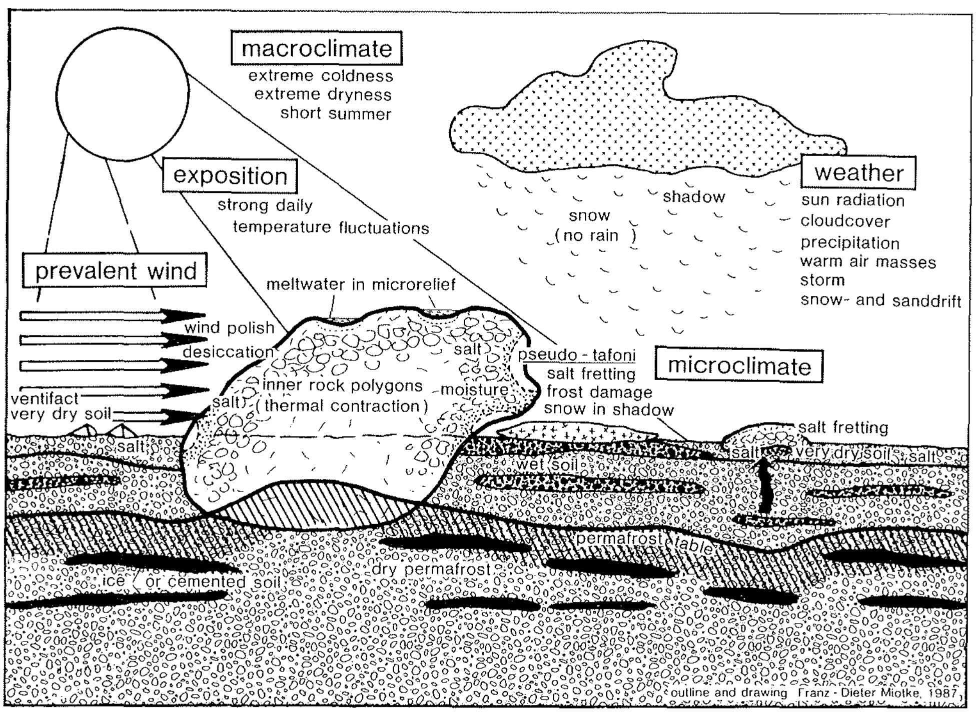


Fig. 2: Rock weathering in Continental Antarctica follows specific local conditions. Macroclimate and accompanying weather conditions set the general frame. Exposure to sun and prevailing winds and, in addition, different moisture contents create most diverse microclimates with weathering processes varying considerably. — Thermal contraction causes "inner rock polygons" which open the rock to frost- and salt fretting and allow lichens to invade the rock interior.

Abb. 2: Die Gesteinsverwitterung in der kontinentalen Antarktis gehorcht spezifischen lokalen Bedingungen. Das Makroklima und die zugehörigen Wetterbedingungen setzen den allgemeinen Rahmen. Exposition zur Sonne und vorherrschende Windrichtungen und zusätzlich verschiedene Feuchtigkeitsgehalte schaffen sehr unterschiedliche Mikroklimate, in denen die Verwitterungsbedingungen erheblich variieren. Thermische Kontraktion verursacht "inner rock polygons", die innere Gesteinsbereiche für Frost- und Salzsprengung öffnen und auch den Flechten erlauben, in das Gestein einzudringen. Feuchtigkeit wandert aus dem Auftauboden in das Gestein. Vertiefungen im Mikrorelief der Gesteinsoberfläche sind zeitweise mit Schmelzwasser von Schnee gefüllt, der auf das sonnenerwärmte Gestein geweht wurde. Die resultierende Wabenverwitterung kann auf Kristallingestein und auch im Sandstein beobachtet werden.

3.2 *The Physical Weathering Processes*

Disintegration of solid rocks due to thermal expansion or thermal contraction, tectonic forces, pressure release, tidal forces, and the effect of living organisms is a prerequisite for deeper-reaching chemical weathering. Only where water and gases through cracks find their way into the otherwise impermeable rock, chemical reactions can start decomposing rock minerals. Even in the presence of water, frost damage is only possible where openings or cracks already exist. The same applies to salt fretting.

3.3 *"Inner Rock Polygons"*

In ice-free continental Antarctica, rocks are under additional stress due to intensive thermal contraction as a consequence of very low winter temperatures sinking even below –60° C. The resulting tensions which crack the interior of the rock form three-dimensional polygons. These "inner rock polygons" I first detected and named when studying sawed-up rocks from various areas of the Dry Valleys and from the Darwin Mountains. In cross-sections these "inner rock polygons" remind of patterned ground, only on a smaller scale.

Cracks run straight through the minerals. Close to the surface these cracks either become much narrower or disappear altogehter (MIOTKE & VON HODENBERG 1983a). These cracks later break open due to frost and salt-fretting.

3.4 *Frost Shattering*

Although soil and rock surfaces in general are rather dry, we must not conclude that frost shattering does not occur at all. A low water content in fine fissures seems to be sufficient to cause frost cracking, at least at the very surface. Splitting-off of either individual crystals or fragments of already cracked rocks is the result of the combined effect of frost and thermally caused tensions.

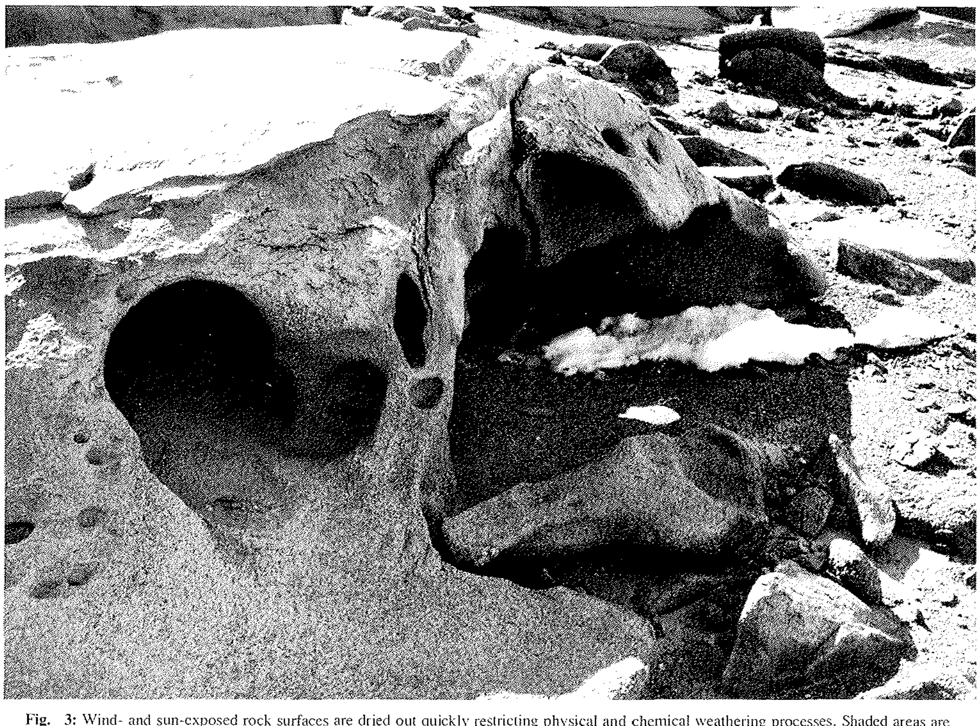


Fig. 3: Wind- and sun-exposed rock surfaces are dried out quickly restricting physical and chemical weathering processes. Shaded areas are more humid and suffer from heavier frost shattering and, in addition, permit longer-term chemical reactions. The aymmetrical shapes of Antarctica's pseudotafoni are due to these facts.

Abb. 3: Wind- und sonnenexponierte Gesteinsseiten trocknen schnell aus, so daß sowohl physikalische als auch chemische Verwitterungsprozesse eingeschränkt werden. Schattenpartien sind feuchter, werden stärker frostverwittert und erlauben für längere Zeiten chemische Reaktionen. Die Pseudotafoni der Antarktis verdanken diesen Tatsachen ihre asymmetrischen Formen.

3.5 *"Pseudotafoni"*

Where prevailing winds rapidly and constantly dry out rock surfaces, the latter stay relatively smooth, whereas leewards, where moisture can work for a much longer time period, rocks are disintegrated to a high degree. Sometimes chemical weathering processes may also play a role though a minor one (see Fig. 3).

The examination of the inner rock structure by means of thin slices did not reveal loss of material nor case hardening. Some igneous rocks, though, showed progressively weathered feldspars near the surface. Igneous rocks on older erosion surfaces in Antarctica often have forms quite similar to tafonis known from semiarid, warm climates. The Antarctic shapes have a different origin, they are not formed by the same weathering processes. Consequently, the Antarctic forms should properly be termed "pseudotafoni", if we want to use this expression at all

3.6 *Chemical Weathering in Continental Antarctica*

The velocity of chemical decomposition of rocks largely depends on the occurrence of temperatures clearly above freezing and on the presence of moisture. Both factors are rare in Continental Antarctica. Moreover, the soils do not contain organic acids nor higher CO_2 concentrations common in vegetation-covered regions of the Earth.

However, iron-oxide-stained rock surfaces and accumulated salts, part of which at least are residuals of rock decomposition, clearly demonstrate that chemical weathering does exist in Antarctica! (MIOTKE & VON HODENBERG 1983a).

The main factors of chemical reaction are the following:

3.6.1 Temperatures

In the summer, especially rock surfaces facing north are warmed well above the freezing point, locally reaching temperatures of up to 30° C. These peak temperatures were measured under a clear sky only and around high noon. Such high temperatures cannot be obtained every day during the short summer, however, and do not last for more than a couple of hours. But during this time, chemical weathering takes place in quite similar a way as in temperate regions. And these short periods of accelerated chemical activity add up over many thousands of years (see Fig. 4).

3.6.2 Moisture

Due to a nearly complete lack of rainwater the only liquid water sources on the surface are melted snow and melted ice. Short-term water saturation of the upper soils and rocks occurs only near the edges of snow patches where re-radiation from the ground melts the snow. Locally within the active layer, existing ice can also be melted. Directly under the snow, the soils are very dry with local ice.

The soil is generally very dry near the surface, the water content often being less than 0.1%. Below a depth of about 10 cm, humidity may increase locally up to several percent providing enough water for chemical weathering processes. In places, ice was found to form a crust in about 50 cm depth. A trench, which we dug, was soon flooded after the ice had thawed.

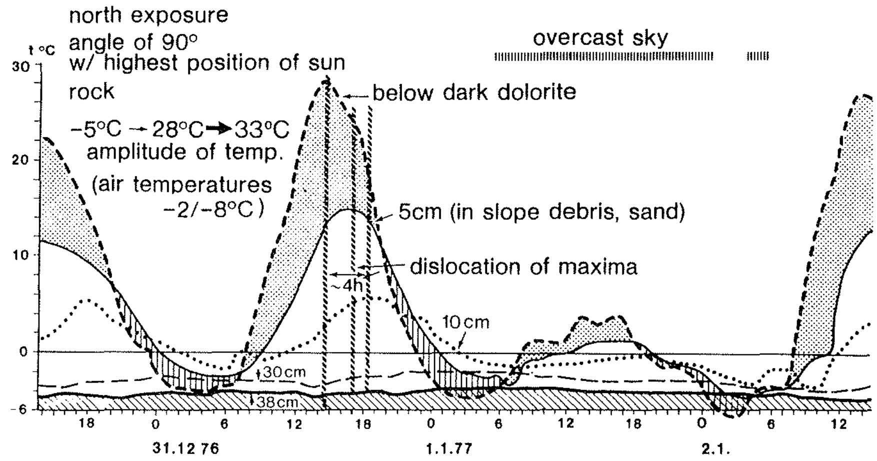
3.7 *Salts as a Product of Chemical Weathering*

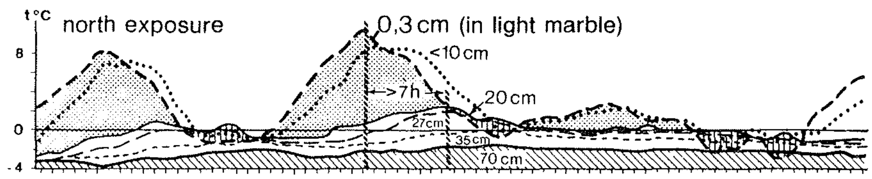
In the summer, rock and soil moisture from deeper levels penetrates upwards into dried out horizons to a few centimeters below the surface where inner evaporation causes transported ions to form salt crystals. There is a clear correlation between higher temperatures just beneath the surface, lower humidity and accumulated salts (MIOTKE & ON HODENBERG 1983a).

Cold soil air contains very small amounts of water. When soils and rocks are warmed up close to the surface, the relative humidity of air in the soil decreases dramatically. In such an extremely low air humidity within the soil some minerals originate which have so far been known to exist only in hot deserts. My colleague, R. von Hodenberg, a salt mineralogist, with whom I worked together, identified, for example, bassanite ($CaSO_4 . 1/2 H_2O$), natrojarosite ($NaFe_3(OH)_6 (SO_4)_2$) and also a completely new mineral discovered on the Earth for the first time, a Na-Ca-double sulfate ($Na_2Ca_2(SO_4)_3 . 3H_2O$).

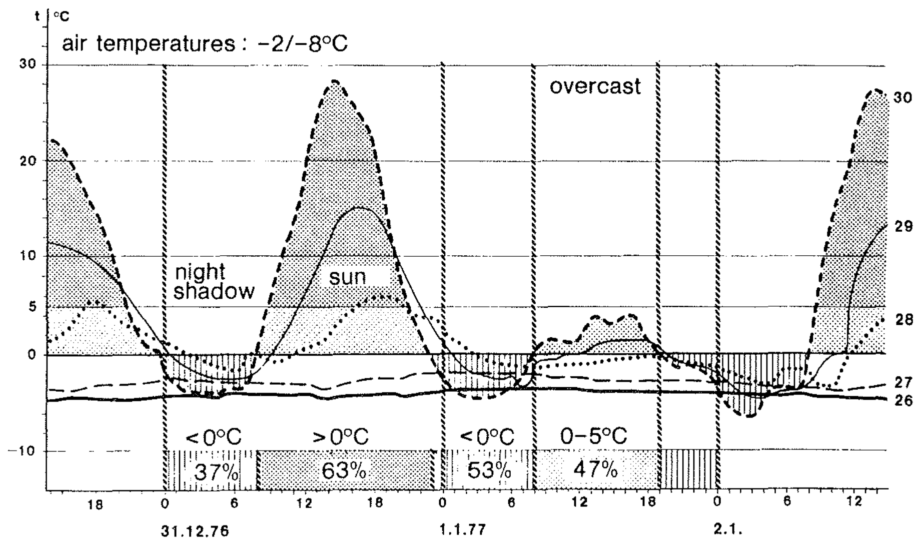
The origin of salts in soils and rocks of Antarctica has been discussed for a long time. Many authors favor the

NUSSBAUM RIEGEL, TAYLOR VALLEY/ANTARCTICA





26 38cm depth in fine grained material
27 30cm depth in fine grained material
28 10cm depth in fine grained material
29 5cm depth in fine grained material
30 directly below rock plate (50° tilted) north exposed



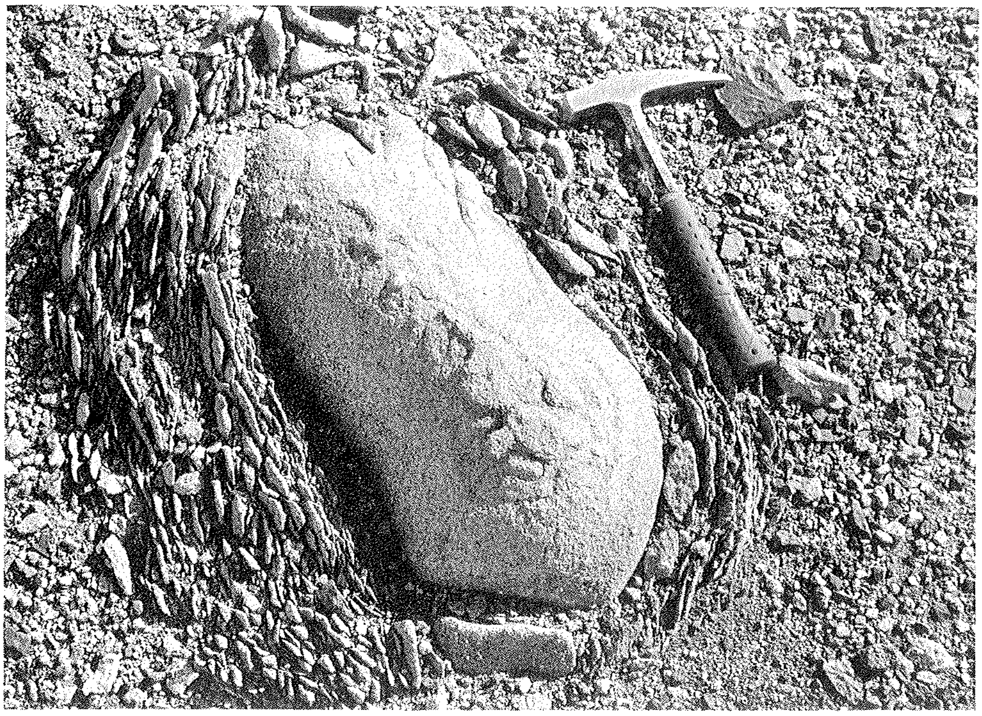


Fig. 5: Rocks protruding from pavements are attacked by different weathering processes. Exfoliation caused by pressure release, temperature-induced shrinkage, frost and salt fretting and additional chemical reactions break up the rock structure into small particles to be blown away by heavy winds until rocks are levelled to pavement surfaces.

Abb. 5: Gesteine, die über die Steinpflasteroberfläche hinausragen, werden von verschiedenen Verwitterungsprozessen angegriffen. Durch Entlastungsspannung verursachte Exfoliation, temperaturverursachte Schrumpfung, Frost- und Salzsprengung und zusätzlich chemische Reaktionen zerbrechen die Gesteinsstruktur in kleine Partikel, die von starken Winden ausgeblasen werden, bis die Gesteine bis zur Steinpflasteroberfläche "eingerumpft" worden sind.

idea that salts are blown in from the sea or from volcanoes. Our studies have shown that in-situ weathering contributes to the local composition of salts more than just a few percent. This result is supported by the compilation of literature data from all over the Antarctic continent, which shows that salts from different areas are of specific ion compositions.

In the absence of surface water flow and because of restricted infiltration due to a high permafrost table not very much selective outwash of salts can be expected either. Salts are accumulated in the vicinity of weathered rocks. Consequently, salt compounds in general reflect the outcropping rock varieties of the area.

3.8 *Factor Time (Length of Weathering)*

Beside spatial alterations we also have to keep in mind the length of time certain processes have been going on already. In general, higher erosion surfaces are older than lower ones, which is also true of the Dry Valleys.

On high erosion levels, as in the Olympus Range, less resistant rocks are largely weathered away leaving a high percentage of dolorites. Salt concentrations, especially underneath rocks, are normally much higher on older surfaces than on lower terraces along the main valleys. The older landsurfaces are, the longer weathering has

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Fig. 4A: Daily temperatures in different depths of dark dolorite and light marble.
Fig. 4B: During clear summer days temperatures close to the surface reach high percentages above 0° C.

Abb. 4A: Tagesgang der Temperaturen in verschiedener Tiefe von dunklem Dolerit und hellem Marmor.
Abb. 4B: Bei klarem Sommerhimmel liegen die oberflächennahen Temperaturen zu einem hohen Prozentanteil über 0° C.

Fig. 6: Rock temperatures under summer radiation vary considerably in the course of a day. Maximum temperatures reach 30° C, but when rock surfaces are shaded the measured values drop fast and dramatically. Thermistors are read at least every 20 minutes around the clock for several days.

Abb. 6: Während der sommerlichen Einstrahlung variieren die Gesteinstemperaturen im Tagesgang sehr stark. Maximale Temperaturen der Gesteinsoberflächen erreichen 30° C, sinken aber sehr schnell und tief, wenn die Gesteine beschattet werden. Die Thermistoren wurden ganztägig über mehrere Tage wenigstens alle 20 Minuten abgelesen.

taken place, the richer in salt content rocks and soils close to the surface become because outwash by surface flow is lacking.

3.9 *Biologically caused chemical weathering*

Excepting a few tiny spots on raised coastal beaches where moss patches can exist there is no vegetation cover on rocks and debris in Continental Antarctica. The terrestric fauna is also restricted to microforms living in small ecological niches. Therefore, in general, biological weathering cannot be of great importance in Dry Valley areas. On the other hand, chemical weathering caused by algae, lichens etc. living locally on or within rocks cannot be ignored completely. However, we do not yet know very much about ion exchange reactions between organisms and rock surfaces. Even information about pH data at the very contact surface of plants on the rock minerals are lacking.

4. CONCLUSION

All the factors considered in this paper are of major importance for relief forming processes and many have at least some relevance to biological problems as well, because they represent the microenvironment which is the basis of both sciences.

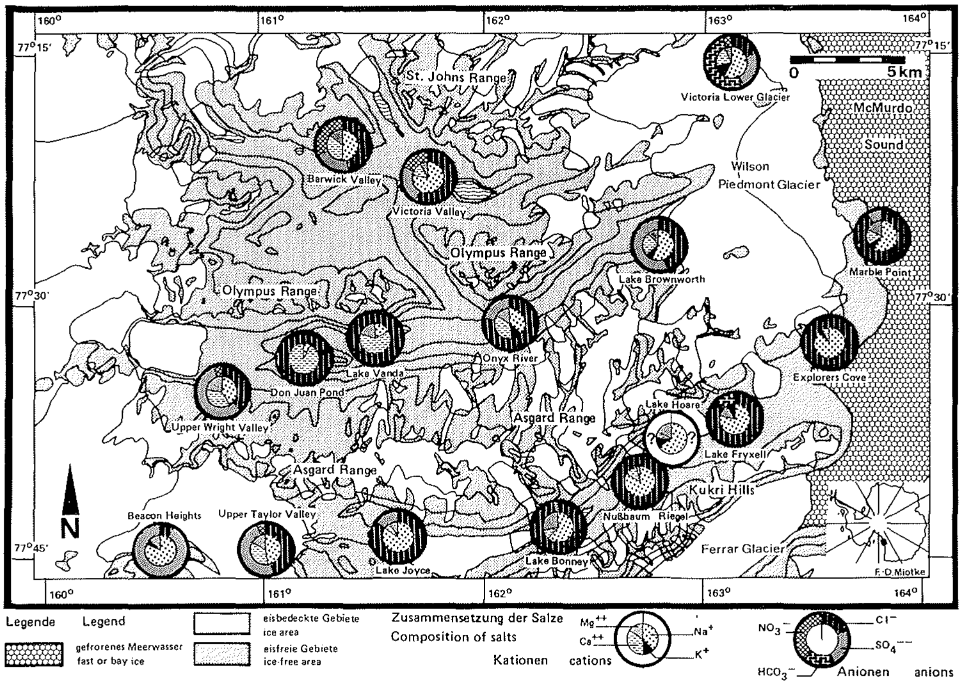

Fig. 7: Ion composition of salts in soils and rocks in Dry Valleys, South Victoria Land (representative mean data according to literature). Cation as well as anion composition show locally different pictures. Due to short distance from coast sodium chloride pecentages are predominant here: farther inland they decrease or are nonexistant. There salt compositions are mostly determined by outcropping rocks from which they weather out.

Abb. 7: Die Zusammensetzung der Anionen und Kationen ist örtlich sehr verschieden. Nahe der Küste zeichnet sich eine Prädomination der Natriumchloridanteile ab, die aber weiter weg von der Küste nicht so deutlich oder überhaupt nicht zu beobachten ist. Dort werden die Salzzusammensetzungen von den anstehenden Gesteinen festgelegt, aus denen sie verwittern.

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