Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 62 (1969)

Heft: 2

Artikel: Stress-induced weathering of rock masses

Autor: Gerber, Eduard / Scheidegger, Adrian E.

DOI: https://doi.org/10.5169/seals-163705

Eclogae geol. Helv.	Vol. 62/2	Pages 401–415	With 16 figures in the text	Basle, Dec. 1969

Stress-Induced Weathering of Rock Masses

by EDUARD GERBER[1]) and ADRIAN E. SCHEIDEGGER[2])

ABSTRACT

The thesis is advanced that stress-induced effects contribute significantly to the decay of rock masses. An observational and theoretical confirmation of this thesis is presented.

1. Introduction and General Postulate

It becomes more and more evident that significant advances in geomorphology can be obtained only if the observations in the field are supplemented and extended by theoretical considerations about the stress conditions particularly near the surface of the earth. In this instance it is possible to proceed in two ways. First, one can test a hypothetical theory for a case which has been well investigated and where measurements can be obtained, and second, one can review a large quantity of observational material from which typical instances can be selected which are representative of general ideas of the stress conditions (GERBER, 1969).

Here we shall proceed along the second possibility outlined above. Apart from erosion proper, a process called «weathering» affects the form of the surficial features of the earth. On a steep rock formation, where no screes can accumulate, «weathering» has a significantly different character than on a less steep slope, on which a scree cover is possible. We shall concern ourselves in this paper only with steep rock formations. On such rock formations, weathering proceeds only to the formation of coarse, loose material which is not further reduced *in situ*, since it quickly falls away unless it somehow gets wedged together to form stable towers.

Generally one has to distinguish between «exogenic» and «endogenic» weathering. Under the influence of atmospheric effects, the cohesion between rock-masses is weakened. The influence of the atmosphere depends very much on the type of rock and its laminations. The influence of the atmosphere causes «exogenic» weathering.

However, every rock mass is also subject to a stress field which may contribute significantly to its decay (weathering). We call the stress-effects «endogenic» weathering. In fact, VOIGHT (1966) has already noted that, if large horizontal stresses are present, there may be a relation between the latter, the local tectonics, and «weathering». We wish to propose that the effect of stresses on weathering is much more

[1]) Dr. E. GERBER, Schinznach-Dorf, Aargau, Switzerland

[2]) Professor A. E. SCHEIDEGGER, University of Illinois, Urbana, Illinois, USA

widespread than commonly believed. Thus, it is the general thesis of this paper that endogenic (stress-induced) effects contribute significantly to the decay of rock masses and to adduce an observational and theoretical confirmation of this thesis.

2. Observations

a. Internal Stress

Every large rock mass is subjected to internal stress, which, if there is a surface exposure, will be subject to certain boundary conditions. These stresses which are manifest near a surface are often termed «residual» stresses. In a folded mountain range, like the Alps, these stresses may be originally of tectonic origin, or they may be induced by pressure and temperature variations upon passage from the interior of a mountain range to the surface. Near the surface, the existence of these stresses may be manifest in fissures and laminations. Just as in a tunnel, where in a rock burst a

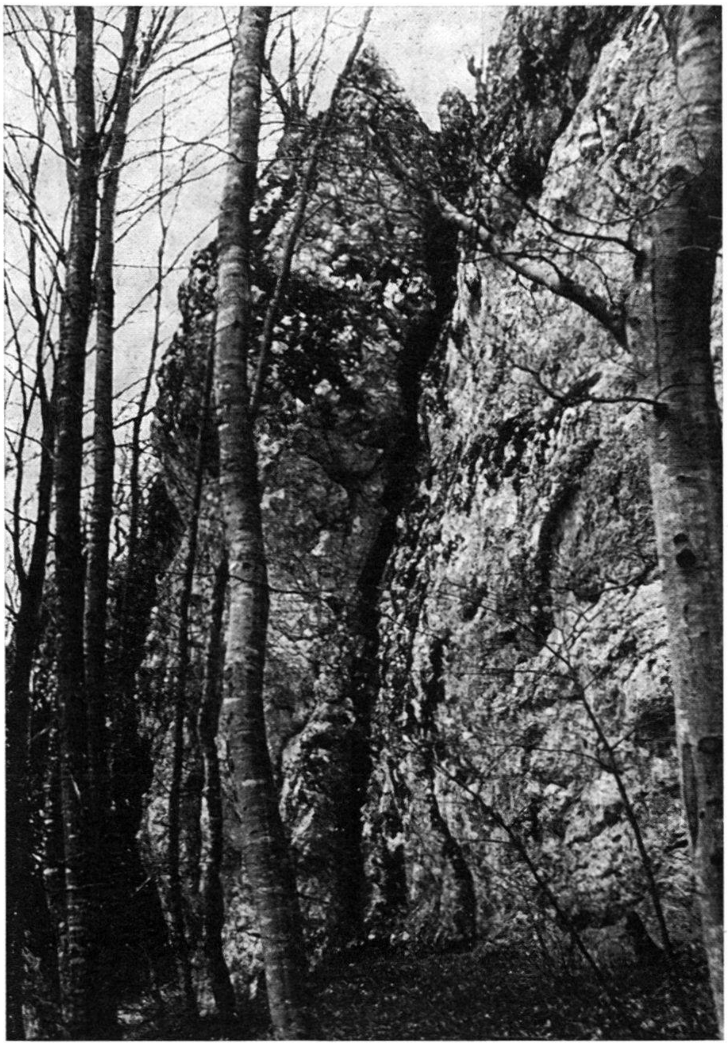

Fig. 1. Tension cracks and break-offs on a rock wall above a friable layer. Gisliflue, Swiss Jura Mountains.

whole plate of rock may be loosened, the bursting off of laminations parallel to the surface may be observed. (Fig. 1)

A further stress-induced «weathering»-process may be due to the structural form of a particular rock mass. The higher such a rock mass, the larger will be the overburden pressure; the steeper a slope, the larger the stresses in the slope-surface. These slope-stresses will always increase from the top to the toe of the slope. They depend, in essence, on the geometric form of the rock mass.

Residual stresses and form-induced stresses constitute the two ways in which the tectonic stress field contributes to the «weathering» of rock masses.

b. Rock Walls

Let us consider first vertical walls. In essentially loose material with slight cohesion, as in vertical canyon walls consisting of loose gravel cemented with argillaceous marl, a height of 10 m is sufficient to create such stresses in its toe that it collapses. In

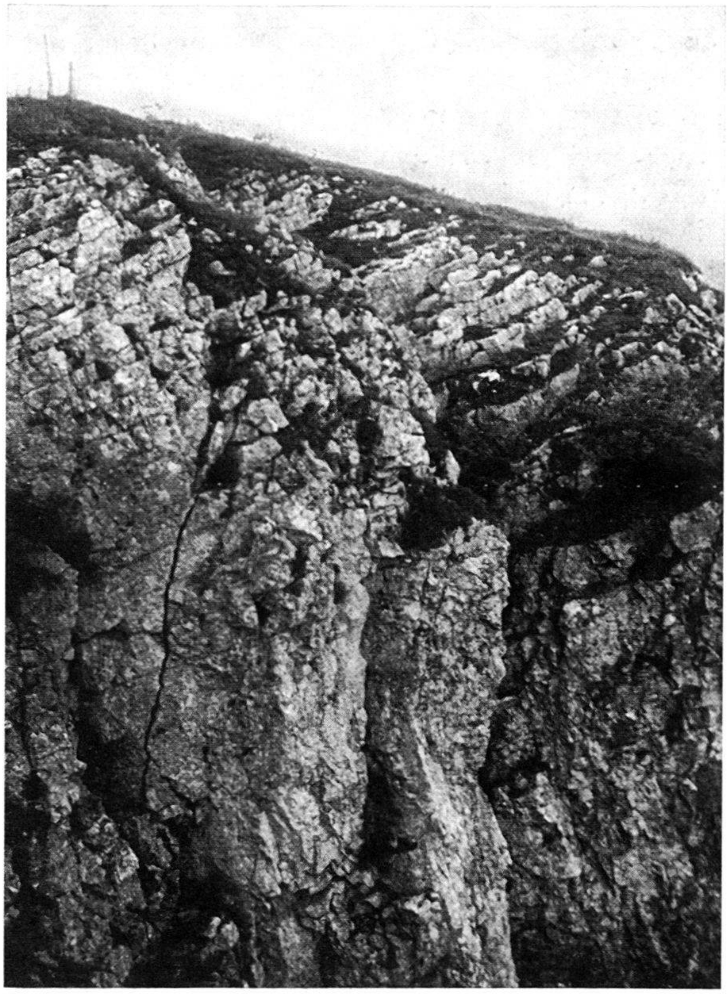

Fig. 2. Weathering of the uncompressed upper part of the rock wall – the strata are clearly visible. In the lower compressed section of the rock wall laminations parallel to the surface are predominant with vertical clefts. Rötiflue, Swiss Jura.

pure rock, the self-supporting strength is such that high walls are possible, as is a matter of self-evidence since otherwise the high cliffs observable in the Alps would not be possible.

However, one cannot regard the form-induced stresses by themselves, but they must be considered in context with other weathering factors. In this instance, form-induced stresses are of paramount importance. Rocks, already weakened by atmospheric effects, which may be under residual stresses, are further subject to form-induced stresses which are always largest at the foot of the wall. Hence, a wall begins to «weather» always near the bottom. A wall, created by some faulting or similar process, does not tend to become oblique, but remains vertical. Only if there are pre-existing oblique surfaces with a reduced shearing-strength can the formation and maintenance of vertical high walls be precluded. This occurs, for instance, in the case of oblique layering (Fig. 2) so that steep walls occur particularly at the break-off (front) of the layers.

If the material at the bottom of a wall cannot support the over-burden pressure and deforms plastically, e. g., limestone overlying soft marl, then it will be partially pressed out by the overlying weight. As a consequence of the yielding base the overlying rock will be under stress which, if it exceeds the tensile strength of the rock, will result in fissures (Fig. 3) and breakoffs. Sometimes the decay results in the formation of blocks which are separated from the compact massif of rocks by fissures. This is often observed on rock-spurs and rock-walls, where a series of «towers» may be found in front of them (Fig. 4, 11).

Fig. 3. A-steep wall at the front, B-steep wall in the cross section, C-surface parallel to the layers, D-undercut layers. Gemmipass. Bernese Alps, Switzerland.

Fig. 4. Tower at the end of a massiv. Horizontal strata and vertical clefts. Ferdenpass, Wallis, Switzerland.

c. Summits

As a contrast to mountain massifs with a relatively flat top, as they are often seen in gently-dipping limestone layers, one may consider pyramidal summits which are connected by catenoid-shaped ledges.

We shall not discuss here the possible creation of such summits from a «primeval surface» (or whatever the «first» surface may have been). We only mention the observation which became obvious by field or map studies, indicating that pyramids with three or four «ledges» occur very often. Pyramidal summits are features of watersheds, either on a summit-line from which valleys leave in opposite directions, or between two parallel valleys (Fig. 5). Near a watershed, water (Fig. 6) or, in high country, snow collects itself. The glacial cirques particularly are characterized by a circular rock-frame. Without discussing the formation of such glacial cirques in detail, we wish to mention that their circular form is statistically particularly stable.

If the round hollows grow, it is impossible for them to completely cover a surface. The pyramidal summits are the «leftovers» between such round hollows and therewith also the nodes of the watersheds (Fig. 7). In pyramids with three ledges, symmetrical forms are not rare. During the aggrandizement of the glacial cirques, the ice does not only act as a means of erosion, but also as one of transportation for the removal of the debris falling off the steep walls, so that no scree slopes can be formed on the foot of such walls.

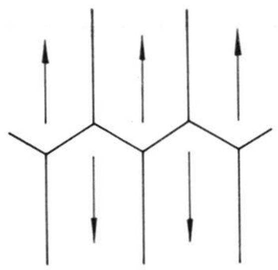

Fig. 5a. Pyramidal peaks on the watersheds between valleys resulting in a zig-zag summit-line (schematic).

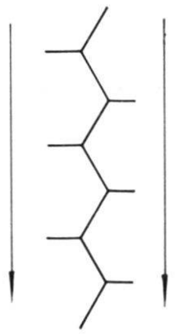

Fig. 5b. Pyramidal peaks between two parallel valleys. A part of the watershed peters out as a rock ledge (schematic).

Fig. 6. Erosion funnels on the front of a long ledge. Mile 1118 Alaska Highway, Yukon Territory, Canada.

Let us consider a pyramidal peak (Fig. 9, 10). One sees thereon a central surface and two flanks on which is the watershed. The central surface, which serves as a water (ice) collector, is often hollowed. The rock at the very summit does not have a supporting function. It can decay freely; often a V-shaped breakoff is observed (Fig. 8, 9, 10). Towards the bottom of the peak the stress increases and is largest at the foot.

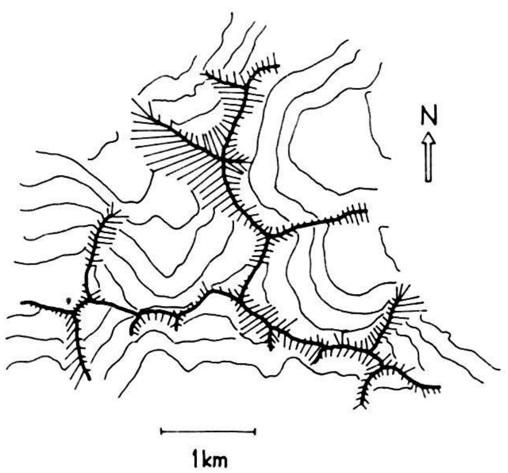

Fig. 7. Plan view of pyramidal peaks with three ledges. Hühnerstock, 3307 m, Aar-Massiv, Swiss Alps (Schematic).

The flanks which form the watershed, either form a catenoidal ledge passing over to the next summit, or peter out as a rock-ledge (Fig. 11). As a part of the structure of the whole peak, these ledges form apparently lateral supports subject accordingly to stresses. If such a ledge peters out, i.e., if it does not connect to a neighboring peak, it may show tensional cracks and fissures, if there is a fault system across it. The ledge is thereby split into individual blocks and towers.

On single high peaks, on whose summits there are no erosion funnels, i.e., where weathering is predominant, complete pyramidal forms are usually created by selection of the statically most stable shape, thus resulting in cones. If this occurs on a very small scale, one has earth pillars (Fig. 12). If there are erosion funnels at the bottom of a summit, one sees the pyramids whose flanks form supports. This is particularly evident if the funnels contain ice (glacial cirques) (Fig. 9).

Often, it is possible to observe similar break-offs at the top of a ledge which ends abruptly.

d. Summary of Observations

Many features in high mountain country have an imposing appearance. However, they do not give the impression that they are ready to decay. To the contrary, they appear in their grand design astonishingly stable and give the impression of a statically proper «design». The often steeply ascending lofty peaks are most durable. It is usually only the outermost layer which is subject to progressive decay.

In this observation one can recognize a selection of statically well-built forms. All processes, whereby unstable decay-prone forms are transformed into more stable ones, occur very rapidly. If these decay-processes have run their course, a more stable form remains which is able to subsist for a relatively long time and decays only then, when weathering and erosion have produced new unstable forms. This selection of statically stable forms is only somewhat affected by the layering or lamination of the rock and by pre-existing surfaces of weakness. Conjugate stress-induced fracture surfaces may transgress rock walls at angles of 40–60° to the horizontal and produce groups of V-shaped forms within a rock wall (Fig. 8, 9, 10, 13).

The evaluation of surficial features does not cease until the final form of all denudation processes is reached: a horizontal peneplain. However the latter may be

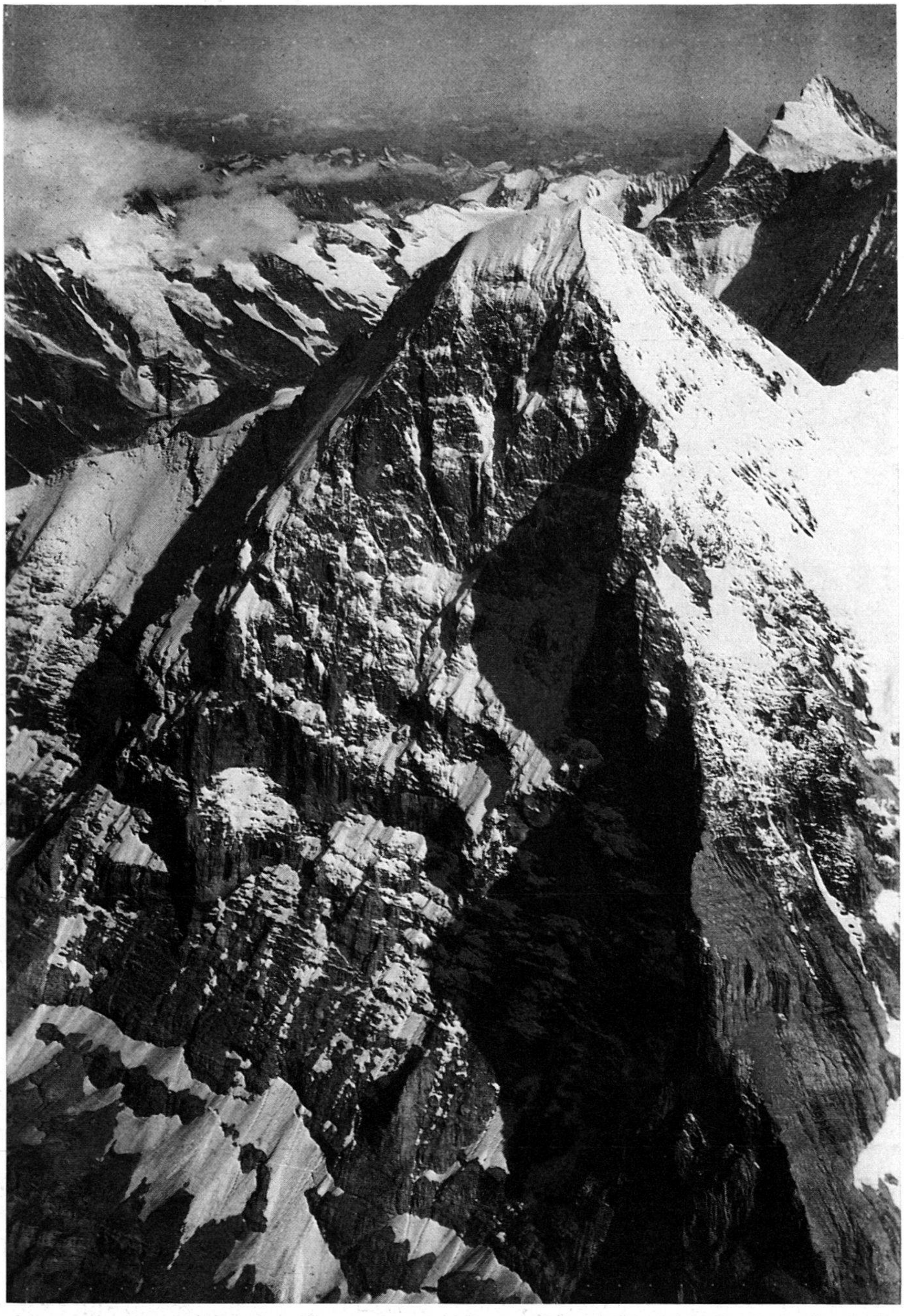

Fig. 8. Peak with central excavation. Limestone rocks. Eiger, north side, 3970 m, Bernese Alps, Switzerland. Photo Swissair.

Fig. 9. Pyramidal peak with central excavation (A) which serves as an ice collector and two flanks (F). Crystalline rocks. Lenzspitze, 4294 m, Wallis, Swiss Alps.

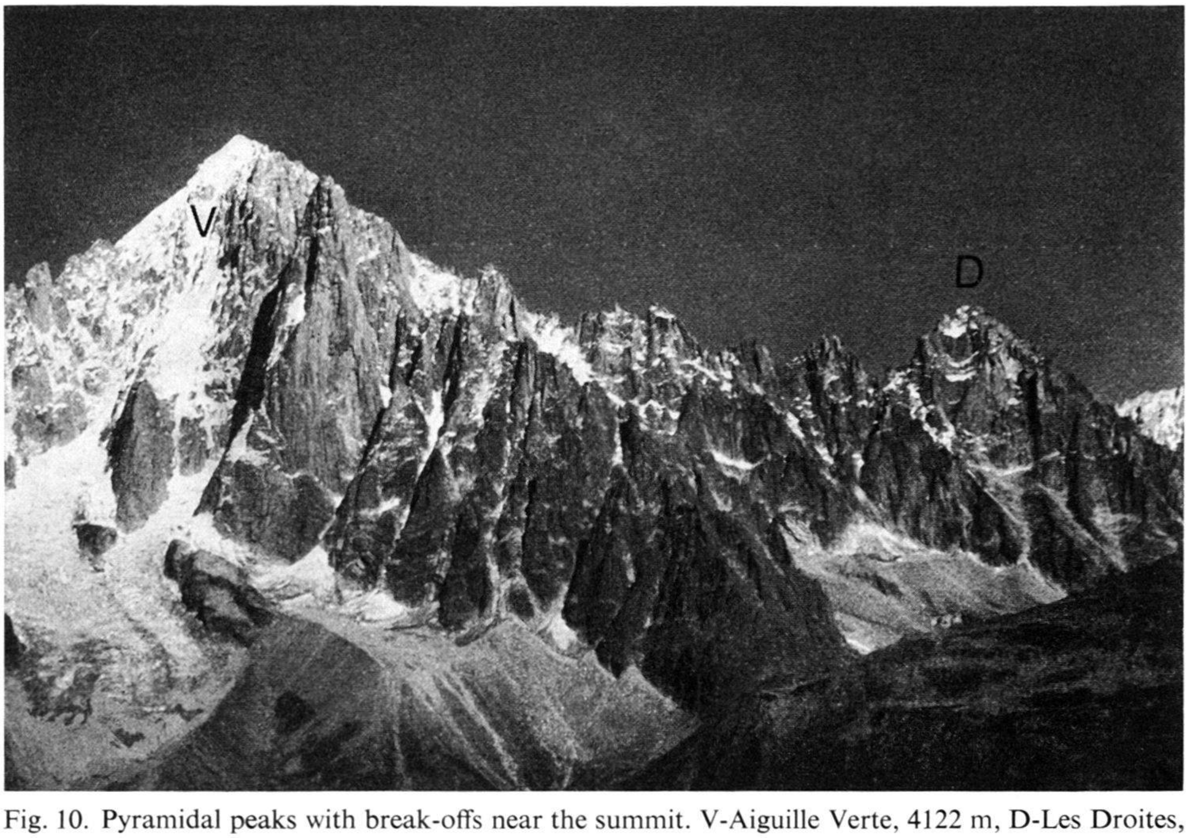

Fig. 10. Pyramidal peaks with break-offs near the summit. V-Aiguille Verte, 4122 m, D-Les Droites, 4000 m, Mont-Blanc, France.

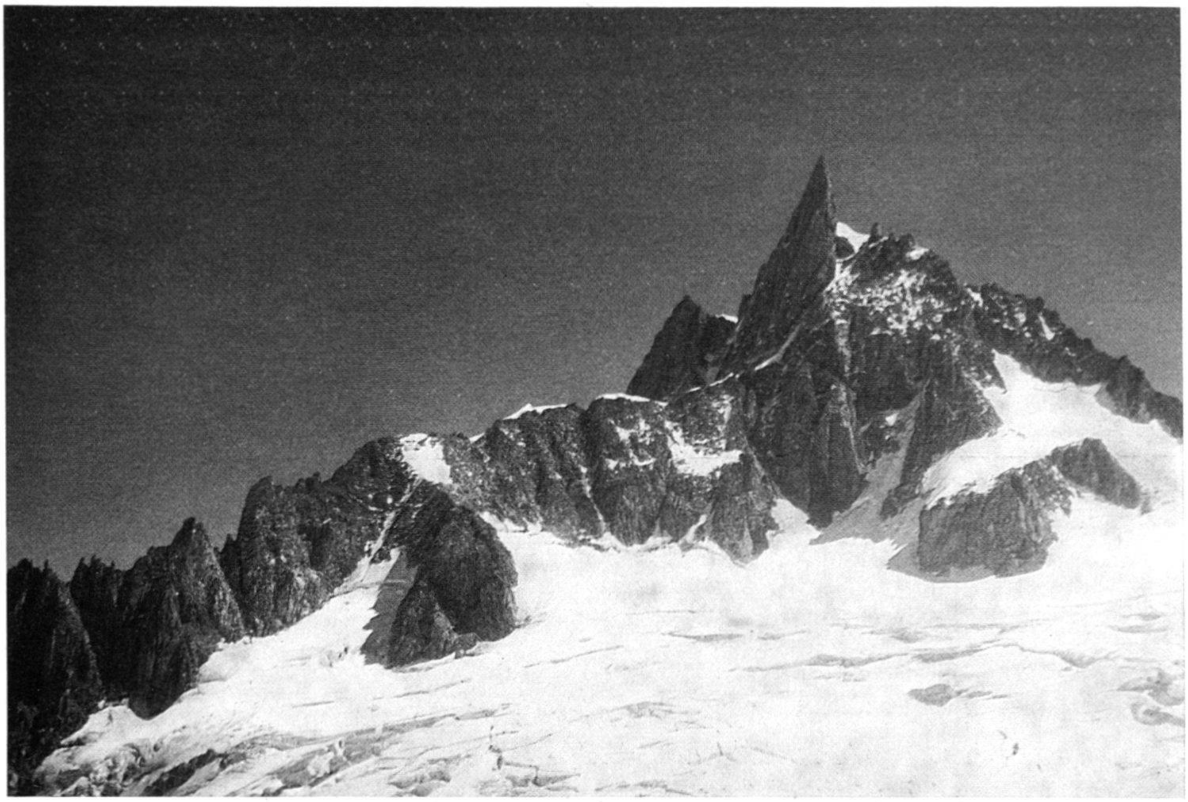

Fig. 11. Ledge o a pyramidal peak with tensional cracks and fissures, split into individual blocks and towers. Aiguille du Géant, 4013 m, Mont-Blanc, France.

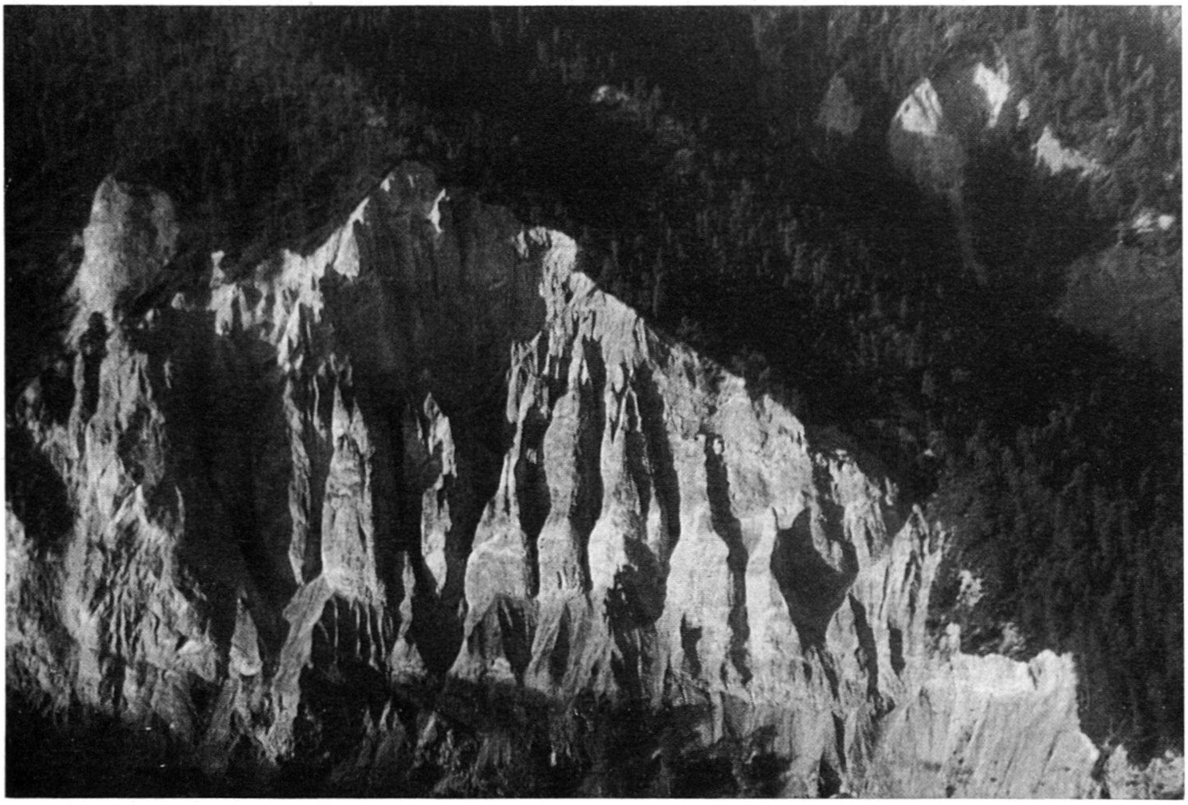

Fig. 12. Earth pillars in slide material and break-off at the top of the end of a ledge. Versam Rhine valley, Swiss Alps.

disturbed again by endogenic processes. The concept of selection of statically stable forms is therefore a relative idea and refers to a particular energy of the relief and valley-density and to a particular rock-material (with all its properties). By the selection of statically stable mountain forms many similar shapes are created within the above-defined framework.

3. Theory

a. Internal Stress

As noted in Section 2, every large rock mass is subject to a tectonic stress field. Near the surface, this rectonic stress field is subject to special boundary conditions which can give rise to stress concentrations. The latter may cause «weathering» apparently due to the action of «internal» stresses.

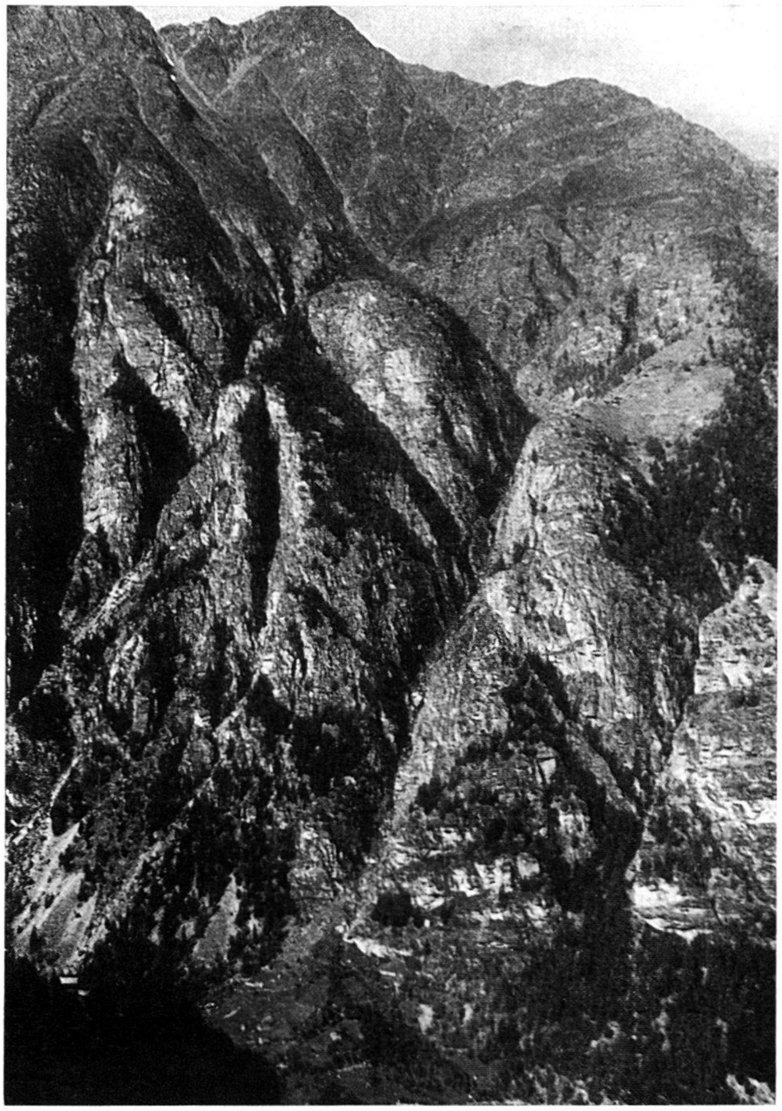

Fig. 13. Conjugate stress-induced fractures in a rock wall. St. Niklaus, Valley of Zermatt, Swiss Alps.

Thus, if a rock mass is buried at a certain depth, it is subject to the stresses at that depth. If it becomes uncovered by geological processes, the stress field will change and give rise to «residual» stresses. The origination of such residual has been studied, for instance, by KIESLINGER (1958) who noted that, if somewhere a free rock-surface is generated say, by the (geologic) removal of some «overburden», a partial stress relief takes place. The stress component normal to the surface will be zero at the surface, and this condition will make itself felt a certain distance into the interior of the rock. Near the surface of a recently uncovered rock mass, the stress state is therefore one of high stresses parallel to the surface. The mass will therefore tend to expand in the direction of the free surface, giving rise to slight arching and therewith a buckling-type of instability. This results in the splitting-off of plates parallel to the surface; the phenomenology of these plates is entirely unrelated to any original stratification that might have been present in the rock. This explains the observations demonstrated in Figure 2.

It has been established for some time that the stress field, at least near (relatively speaking) the Earth's surface, is not a hydrostatic field, but may considerably deviate therefrom (see SCHEIDEGGER, 1963b).

This stress field, because of the boundary conditions prevalent at the surface, must be near one of three possible «Anderson states». Anderson's well-known theory of faulting (see ANDERSON 1942) postulates two potential conjugate fault surfaces in a given tectonic stress system. Evidently, these fault surfaces will have potential traces on the surface of the Earth. It is, thus, indicated to interpret the actual traces of conjugate fault systems, as observed in many places upon the Earth, in terms of the Anderson surfaces of the tectonic stress tensor which was prevalent at the time these faults were created. Since there are geologically three characteristic types of faults possible (normal, i.e. «tensional», overthrust and wrench faults), one has three possible stress states, corresponding to these fault types. In normal faults, the principal direction of the largest compression (P) is vertical, the direction of the smallest compression (T) and the intermediate principal stress directions (B) are horizontal (at right angles to one another); in overthrust faults, the P and B directions are horizontal, the T direction is vertical; and in wrench faults the B direction is vertical and the P and T directions are horizontal. These «Anderson» states are the possible stress states near the surface in geologically undisturbed areas; the deviations and adjustment of these states to local conditions cause the «internal» stress effects.

The modifications of the regular stress patterns by surface inhomogeneities have been studied by STURGUL and SCHEIDEGGER (1968). Accordingly, the most important feature in a notch running across a maximum principal horizontal stress direction is the occurrence of a stress concentration at the bottom of the notch. In a protrusion, stress concentrations occur at the shoulders of the protrusion, and a stress reversal may occur at the top. These general patterns characterize the effect of «internal stresses» on surface irregularities.

Applications of this general theory will be presented in connection with the individual features to be discussed below.

b. Rock Walls

The observations on the decay («weathering») of rock walls have already been compared with possible stress conditions by the present authors (GERBER and SCHEIDEGGER, 1965). In that paper it was estimated that the stress state is such that Mohr-type failure occurs at the bottom of the wall. Meanwhile, STURGUL and SCHEIDEGGER (1967a) have published results on the numerical calculations of tectonic stresses in the vicinity of a rock wall so that the qualitative argument used by GERBER and SCHEIDEGGER (1965) has now been numerically substantiated.

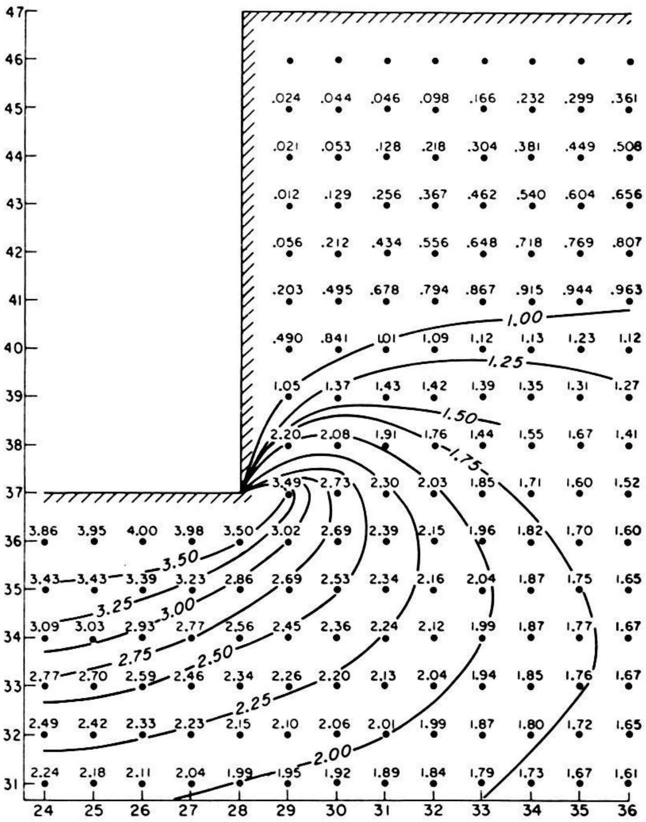

Fig. 14. Lines of equal σ_{max} near a wall (after STURGUL and SCHEIDEGGER, 1967a).

It is therefore quite obvious that there will always be stress concentrations at the foot of a wall in a tectonic stress system as demonstrated, for instance, by the σ_{max} lines shown in Figure 14. (Fig. 8 in STURGUL and SCHEIDEGGER, 1967). In Figure 14, the wall is subject to a horizontal tectonic stress field whose value is unity at infinity. Of interest is also the low value of σ_{max} near the top of the wall; there, σ_{min} (not shown here) becomes negative. The calculations of STURGUL and SCHEIDEGGER (1967) do not take gravity into account; the effect of gravity is simply superposed upon the tectonic stress effect.

The explanation of the observed features outlined in Section 2B follows directly from the stress picture presented above.

Thus, the observation that walls always begin to «weather» near the bottom can immediately be explained by the fact that stress concentrations occur at the foot of the wall, if a tectonic stress is present. It is then clear that the further development of this condition through the action of water and ice must be in the nature of an intensification. The condition is, naturally, enhanced if the bottom layer in a wall is less competent than the layers higher up. If the bottom layer is plastic (marl), the stress state induced owing to the weight of the overlying competent (i.e. with high stress strength) rock is an active Rankine state with outward flow. (Fig. 15) This causes a tension in the overlying rock. Whenever the tensile strength of the overlying rock (which is always very low) is exceeded, a block breaks off leading thus to the «tower» structures. The condition is somewhat similar to that discussed in boudinage by RAMBERG (1955): One has a competent layer between «two» incompetent ones. One incompetent layer is the plastic layer below and the other the air «layer» above the rock. The pressure of RAMBERG's case is, in the present case, provided by the weight of the competent rock.

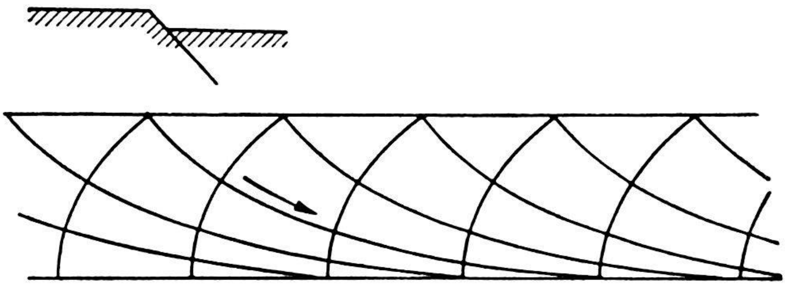

Fig. 15. Active Rankine state.

c. Summits

Mechanically, summits can be regarded as protrusions on a laterally stressed surface. Calculations by STURGUL and SCHEIDEGGER (1967b) have yielded as one of the most characteristic features of such protrusions that (provided the protrusion is high enough) a stress reversal occurs at the top. In mountain areas, the stress state is generally one of a predominant horizontal compression, so that a tensional stress state can be expected at the top of summits.

Since the normal stress near the surface is near zero, and the vertical stress, due to gravity, is a compression, it is seen that, near the top of a summit, a stress state may be created where the horizontal stress normal to the exposed surface is the intermediate stress, the vertical stress (due to weight) the greatest compression and the

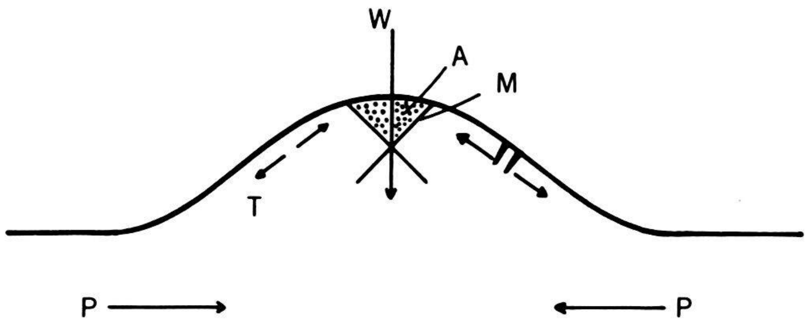

Fig. 16. Stress geometry in a protrusion. W: maximum compression (weight); T: maximum tension; A: breakout; M: Mohr surfaces; P: tectonic stress at infinity; tension cracks on right flank.

horizontal stress parallel to the surface the greatest tension (least compression). Accordingly, one would expect Mohr fracture surfaces normal to the exposed wall, inclined at $\pm 45^\circ$ towards the vertical. This can cause «break-outs» which are the origination of the hollow forms described in the section on observations (see Fig. 16).

In this fashion, the pyramidal forms are the logical end products of the aggrandizement of the stress-induced «break-outs», i.e. of the hollows which, once started, will grow by the «true» weathering—action of wind, water and ice.

As is evident from the geometry of the stress state, such break-outs occur only in summit-walls that are oriented in parallel to the maximum tectonic stress. In walls normal to this direction, no such regularities occur.

The tensional cracks on the ledges are also easily explained by the occurrence of stress reversals in protrusions; in fact, such cracks, according to the usual theories of tension-failure, occur normal to the maximum principal tension. This, then, fits exactly into the stress-geometry for the frontal break-outs (see Fig. 16).

The whole geometry of fractures and break-outs on summits is therefore consistent with a reasonable geometry of the stress.

d. Summary of Theory

The general postulate in this paper is that so-called «erosional» features may, in fact, be triggered by tectonic-stress conditions rather than by the actual effect of ice and water. True, the latter elements will enhance «erosional» patterns, but their prime origination may be caused by «internal» stress conditions.

This thesis was specifically applied to the leafing off of plates on exposed surfaces, to the decay of rock walls, and to the geometry of summits. In all cases, the general characteristics of the stress field could be inferred; the latter appear to be in conformity with the tectonic stress conditions that can be postulated for the respective features.

REFERENCES

ANDERSON, E. M. (1942): *The Dynamics of Faulting and Dyke Formation with Applications to Britain.* (Edinburgh: Oliver and Boyd).

GERBER, E. K. (1969): *Bildung und Formen von Gratgipfeln und Felswänden in den Alpen.* Z. f. Geomorphologie. Suppl. *8*, 94–118.

GERBER, E. K. and SCHEIDEGGER, A. E. (1965): *Probleme der Wandrückwitterung, im besonderen die Ausbildung Mohrscher Bruchflächen.* Rock Mech. and Eng. Geol., Suppl. II, pp. 80–87.

KIESLINGER, A. (1958): *Restspannung und Entspannung im Gestein.* Geol. and Bauw. *24*, 95–112.

RAMBERG, H. (1955): *Natural and Experimental Boundinage and Pinch-and-swell Structures.* J. Geol. *63*, 512–526.

STURGUL, J. R. and SCHEIDEGGER, A. E. (1967a): *Tectonic Stresses in the Vicinity of a Wall.* Rock Mech. and Eng. Geol. *5*, 137–149.

– (1967b): *Some Applications of Elastic Notch Theory to Problems of Geodynamics.* Pure and Appl. Geophys. *68*, 49–65.

VOIGHT, B. (1966): *Beziehung zwischen grossen horizontalen Spannungen im Gebirge und der Tektonik und der Abtragung;* in: Internat. Soc. Rock Mechanics Congress, 1st., Lissabon, 1966, Proc. Vol. 2, pp. 51–56 (Lisboa, Laboratorio Nacional Engenharia Civil).

Manuscript received on December 28, 1968