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# Global measurements of absolute stress

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By absolute rock stress measurements the existence of a *general* horizontal compressive stress field in the Earth's crust is demonstrated; the sum of the horizontal principal stresses linearly increases with depth. The crust is in a state of dynamic stress-equilibrium but areas of instability at places exist. The maximum shearing stress that the bedrock can stand represents a material property and does not increase with depth. The results of extensive absolute stress measurements in the bedrock of Iceland are briefly described and the same from the rock massive of Mont Blanc measured in a rock tunnel between 2500 and 1750 m below the top levels. The mechanism of formation of the mountain is discussed.

A description of the measurement technique and instrumentation would perhaps have been of interest, but time does not permit. Suffice it to say that the stresses in the Earth's crust are recorded in holes drilled into the bedrock from rock faces at ground level or from drifts in mines, underground rooms, etc., and that the absolute stresses are obtained by measuring the changes in stress of the core as it is drilled out. Our Swedish Laboratory, Rock Stress Measurements AB in Stockholm has so far performed some 20000 measurements of absolute stress, about 50 in each hole, most of them in competent rock of granite, granophyre, limestone, sandstone or schist, etc. (Hast 1958, 1967).

## *The existence of a general horizontal stress field in the Earth's crust manifested by absolute rock stress measurements*

Our stress measurements were started in Swedish mines in the early 1950s and for more than 10 years the work was limited to the very old and stable Fennoscandian bedrock area in Sweden, Norway and Finland. The existence of a general horizontal stress field in the Earth's crust was well established here through a great number of measurements, and we accordingly extended our investigation to other parts of the world.

In 1962 the stress distribution was determined in the Earth's crust in Nubia (Abu Simbel Temples), in 1964 in British Columbia in the Peace River area. In the following years expeditions from our Swedish research laboratory were working on Iceland (1967–8), Zambia (1968), Portugal (1968), Jan Mayen and Spitzbergen (1968), Ireland and Liberia (1969), all along the Atlantic coasts. In 1970–71 measurements were performed in the Mont Blanc massif.

## *Horizontal compressive stresses in the crust*

The observed relation between the sum of the horizontal principal stresses $\sigma_1+\sigma_2$ and the depth below ground level at which the measurements were made is shown in figure 1. The diagram includes the values found in all vertical boreholes in Sweden and Finland, 31 points in all. For any particular depth the relation is

$$\sigma_1+\sigma_2 = a+H(0.99\pm 0.03)\ \text{kgf}^{\dagger}/\text{cm}^2, \tag{1}$$

where $a$, the sum of the principal horizontal stresses at ground level in rock as competent as the

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† 1gf k ≈ 9.8 N.

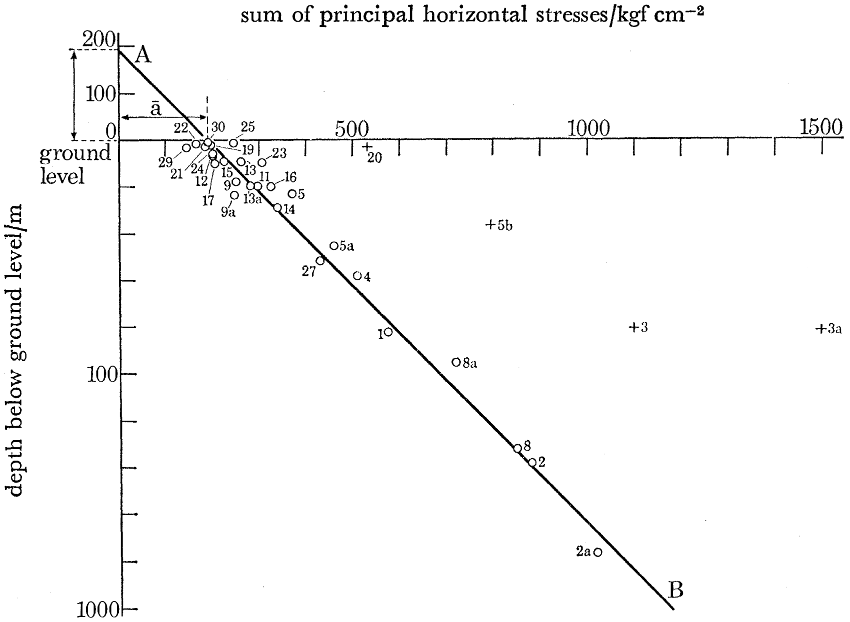


FIGURE 1. Observed relation between the sum of the horizontal principal stresses $\sigma_1+\sigma_2$ and the depth below ground level at which the measurements were made; values from all our vertical holes of measurement in Sweden and Finland.

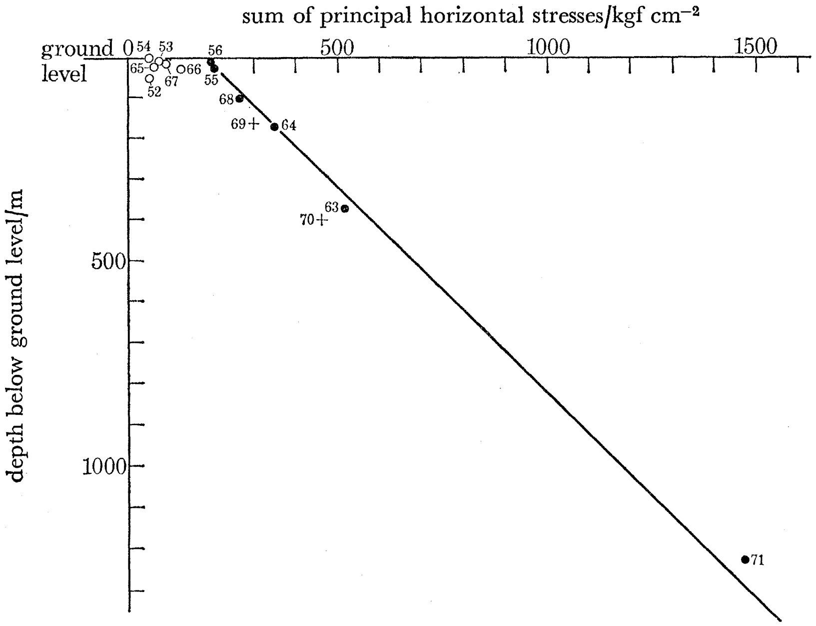


FIGURE 2. Observed relation between the sum of the horizontal principal stresses $\sigma_1+\sigma_2$ and the depth below ground level at which the measurements were made; values from measurements in other parts of the world than Fennoscandia: Spitzbergen (63), Ireland (64), British Columbia (68), Zambia (69, 70), Mont Blanc (71). In surface rocks of low strength as in the volcanic areas on Iceland (points 52 to 54) the magnitude of $\sigma_1+\sigma_2$ is about one half the normal value in competent rocks found in the Fennoscandian area (figure 1). Points 55, 56 concern areas of competent rock on Iceland.

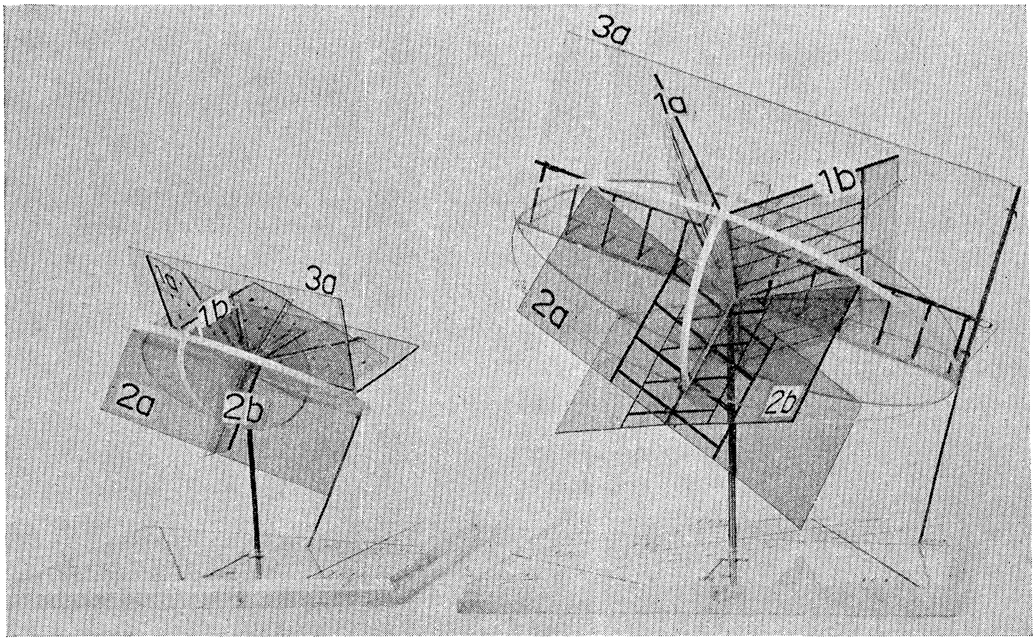


FIGURE 3a. Models of stress ellipsoids characterized by the three principal ellipses; the six planes of $\tau_{\max}$ are $1_{a,b}$, $2_{a,b}$, $3_{a,b}$ all of them at 45° to principal planes. The models represent the state of stress found by absolute rock stress measurements in the Kafue area in Zambia, and located only 40 km from a valley that is considered to be a part of the East African Rift area. The stress ellipsoids were determined 160 (left) and 400 m (right) below ground level. The stresses increase in magnitude and change direction from one level to the other. At 400 m the stresses are: $\sigma_1 = 270$, $\sigma_2 = 190$ and $\sigma_3 = 120$ kgf/cm². The plane of shear $\tau_{\max\ 1a}$ is high (75 kgf/cm²) and inclined at 72° to the horizontal which it intersects in the direction N 16° W; this is about the same direction as the fault lines of the depression areas of Lake Nyasa and Lake Tanganyika. Thus, the East African rift system seems to be an area of very high vertical shear, but no tensile stress.

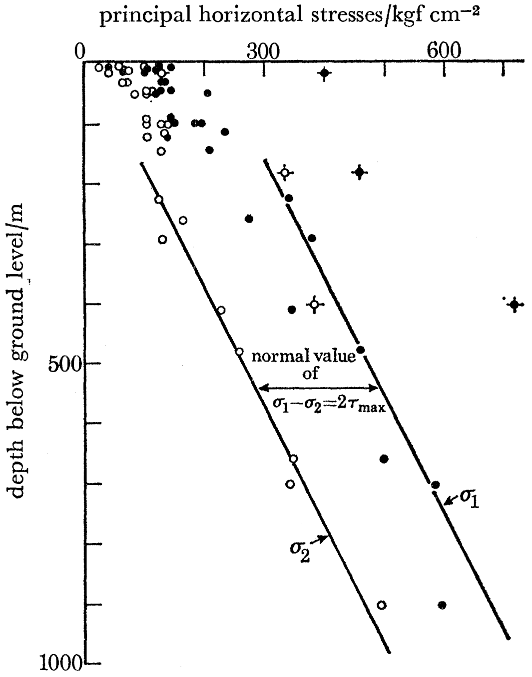


FIGURE 3b. Individual values of $\sigma_1$ and $\sigma_2$ from figure 1. ●, ○ – $\sigma_1$, $\sigma_2$ in normal areas; ✦, ✧ – $\sigma_1$, $\sigma_2$ in over-stressed areas between crust blocks. The difference between $\sigma_1$ and $\sigma_2$ does not increase with depth; this shows that the maximum shearing stress that the bedrock can stand ($\tau_{\max} = \frac{1}{2}(\sigma_1-\sigma_2)$) is a property of the rock.

Fennoscandian bedrock, is 191 ± 1 kgf/cm², and $H$ is the depth of the measuring point below ground level (in metres).

The equation is represented by the line $A$–$B$. The error is calculated by the method of least squares. The formula reduces to, approximately,

$$\sigma_1+\sigma_2 = H+190\ \text{kgf/cm}^2.$$

The horizontal stress, measured as the sum of the principal stresses $\sigma_1$ and $\sigma_2$, increases linearly with depth, and it is obvious that it is stabilized by the weight of the overburden.

Later I shall advance the view that the line $A$–$B$ points to the presence of a state of dynamic equilibrium in the upper part of the Earth's crust. At points in the graph in figure 1 marked by a cross the horizontal stresses are higher than the normal values on the line $A$–$B$ and a situation prevails that points to instability of the crust at these points.

The result of measurements in other parts of the world than Fennoscandia are presented in figure 2. The line $A$–$B$ is the same as that in figure 1.

### *Horizontal shear stresses in vertical planes through the crust*

When the magnitude of $\sigma_1$ and $\sigma_2$ of the stress ellipses differ greatly in a plane stress field, high shearing stresses appear ($\tau_{\max} = \frac{1}{2}(\sigma_1-\sigma_2)$); the same applies when there are large differences between any two of the three principal stresses $\sigma_1$, $\sigma_2$ and $\sigma_3$ of a stress ellipsoid. Except at a few points, $\sigma_1$ and $\sigma_2$ in the Swedish bedrock are horizontal and $\sigma_3$ is vertical and equal to the deadweight of overlying rock.

From the measurements in Fennoscandia it is clear that *the maximum shearing stress that the bedrock can stand represents a material property and does not increase with depth*. The principal stresses $\sigma_1$ and $\sigma_2$ from figure 1 are individually shown in the graph in figure 3b; both increase with depth, but not so the difference, whose magnitude is $2\tau_{\max}$. In areas of competent rock where dynamic stress-stability prevails the recorded maximum value of $\tau_{\max}$ is 120 kgf/cm²; in areas of instability and very good rocks, values of $\tau_{\max}$ of almost 200 kgf/cm² have been found locally.

As figure 3 shows, $\sigma_1$ and $\sigma_2$ often vary greatly in magnitude at depths down to about 150 m although the sum $\sigma_1+\sigma_2$ follows the line $A$–$B$ in figure 1 fairly well. It does not seem possible to make reliable determinations of horizontal movements of the Earth's crust if the points of measurement are located at its surface or less than 150 m below.

### *Horizontal stresses at deep levels in the crust*

We have: $\sigma_1+\sigma_2 = a+H$ and $\tau_{\max} = \frac{1}{2}(\sigma_1-\sigma_2)$; thus

$$\sigma_1 = \tau_{\max}+\tfrac{1}{2}(a+H),$$
$$\sigma_2 = -\tau_{\max}+\tfrac{1}{2}(a+H).$$

$\tau_{\max}$ represents a material property of constant value. At deep levels it will be small compared with $H$ and consequently the horizontal principal stresses $\sigma_1$ and $\sigma_2$ will be more and more equal in magnitude, as deep as equation (1) is valid.

### *The state of dynamic stress-equilibrium and of instability in the crust*

The bedrock in the greater part of Fennoscandia and in the main part of the Earth's crust seems to be in a state of dynamic stress-equilibrium where the magnitude of maximum horizontal stress is demonstrated by equation (1). If for some reason the horizontal stress tends to exceed this maximum value of $\sigma_1 + \sigma_2$, or if the weight of the overburden is reduced, the bedrock becomes unstable and upward buckling occurs, beginning at the surface; the stress is then to some extent released in the upper bedrock, the excess being transferred to deeper levels, the dynamic stress-equilibrium of which will then also be disturbed. Values of $\sigma_1 + \sigma_2$ above the normal magnitude of $\sigma_1 + \sigma_2$ indicate that the rock is horizontally 'over-loaded', and that in the long run it will be unstable and tend to fracture, with a consequent drop in its loading capacity.

In some areas instability in crust might be caused by shear stresses which exceed the strength of the bedrock. In the zones of contact where the deep sea floor meets continental areas high vertical shear in vertical planes and horizontal in horizontal planes often appear. Such stresses have been measured in the Norwegian coastal area to the Atlantic and the Norwegian Sea.

Disturbances of the stability in the crust can be caused by human activity as when large dams for hydroelectric stations are built: rock excavation, the weight of the large water reservoir and changing in its water level. In the bedrock area of many such dams earthquakes have occurred only after the dams were filled – either immediately or after an interval. Thus, it seems necessary to know the state of absolute stress in the crust at places where new stations are to be built.

It would seem that a knowledge of the absolute stress in the upper Earth's crust might be of value also in seismological research – not only for examining the cause and nature of earthquake but, ultimately, as a technique for their prediction, especially in areas where they tend to recur at intervals (Hast 1969*b*).

### *Movements in the crust*

According to our experience of the state of stress and movements in the Earth's crust *the predominant stresses in the upper part of the Earth's crust are in general horizontal but the movements are mainly vertical* or combined vertical–horizontal up to the ground surface. Horizontal movements do occur, for example in the San Andreas fault, in long wide zones of fracturing, but they are uncommon in fractures of a rock massif, unless they occur as sliding in a more or less inclined direction or as a rotation between crust blocks.

The most common type of fractures in the crust is formed by horizontal shear in vertical planes. The fractures start and end in solid rocks which shows that no real movements have taken place. The fractures appear in two directions at right angle to each other, thus forming orthogonal fracture patterns in the bedrock.

In the Earth's crust there exist fractures in vertical planes of large horizontal extent formed by the presence of a high horizontal shear stress field. An example is the floor of the Atlantic Ocean where fracture zones appear in two directions at right angle to each other representing an orthogonal fracture system. Only a great world-wide horizontal shear stress field can produce such an effect; the movements in the area are in general only elastic (Hast 1969*a*).

## ICELAND

The stress measurements in the Iceland bedrock performed in 1967–8 were undertaken to find new material for an investigation of 'continental drift' and 'ocean floor spreading'.

Iceland is surrounded by deep floors – of the Atlantic Ocean in the south, and of the Norwegian Sea in the north. It is possible that in the zones of contact between the deep sea floors and Iceland there are horizontal stresses of different magnitude and direction from those in central Iceland. The stress situation here might indicate whether forces generated in the Icelandic part of the crust area acting on the sea floor, or vice versa.

### *Locations of the points of measurements*

Four of the points are located in coastal areas in the north, southwest and southeast; the fifth, Burfell, lies inland and 10 km west of the volcano Hekla. The measurements were made in vertical bore-holes drilled from the rock face at ground level, in three of the points only a few metres from the shore water-line. The measurements at Burfell were made in a tunnel, 50 m below ground level, belonging to a hydroelectric station under construction. Point 54 is located near Kefflavik, in an area where it is supposed that the Mid-Atlantic Ridge meets Iceland, and point 53 in an area where the Ridge meets the island on its northern shore. Points 55 and 56 are located in southwest Iceland.

### *The strength of the bedrock*

In all parts of Iceland where rock stress measurements were performed, except at points 55 and 56, the rock is of low strength. The bedrock often consists of a series of surface layers from volcanic eruptions at different periods. At places where one basalt stratum overlies another the strength of the surface zone of the lower stratum is often impaired through exposure to air and

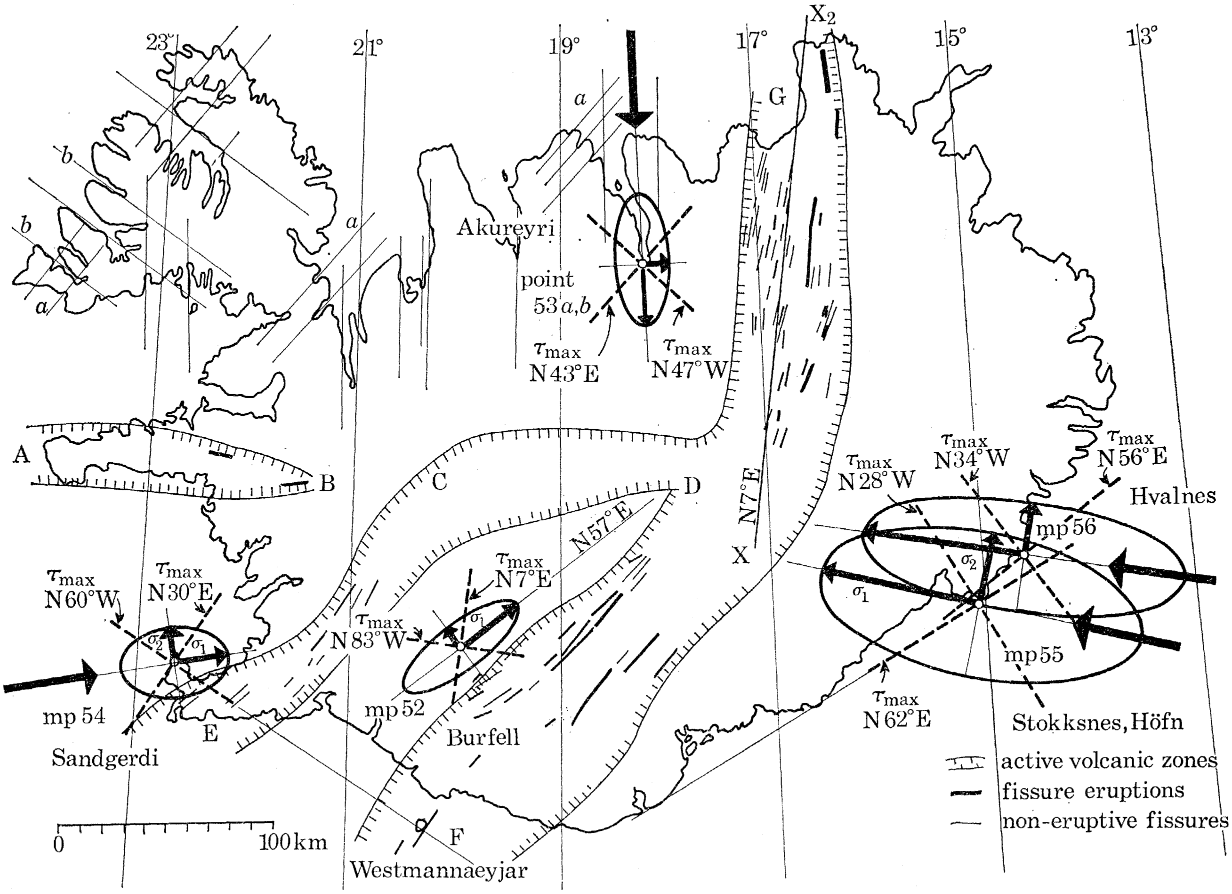


FIGURE 4. Iceland. The locations of five points where absolute rock stress measurements have been performed. On this map the hatched lines – which have been copied from a paper by J. C. P. Walker – demarcate areas of volcanic activity; fissure eruptions and non-eruptive fissures. The stress ellipses show the magnitude and direction of the horizontal principal compressive stresses in the Earth's crust. The stresses are compressive at all points. The ellipses also show the directions of maximum shear stresses or the vertical planes in which they act.

water in the interval between the eruptions. At other places the basalt is weakened through the formation of air bubbles. At points 52 and 53 some layers of the basalt at certain depths has a columnar structure, where the fractures produce local disturbances in the horizontal stress field and in most cases lower horizontal stresses.

In contrast, the bedrock at points 55 and 56 is solid and stable, consisting of gabbro and granophyre, respectively.

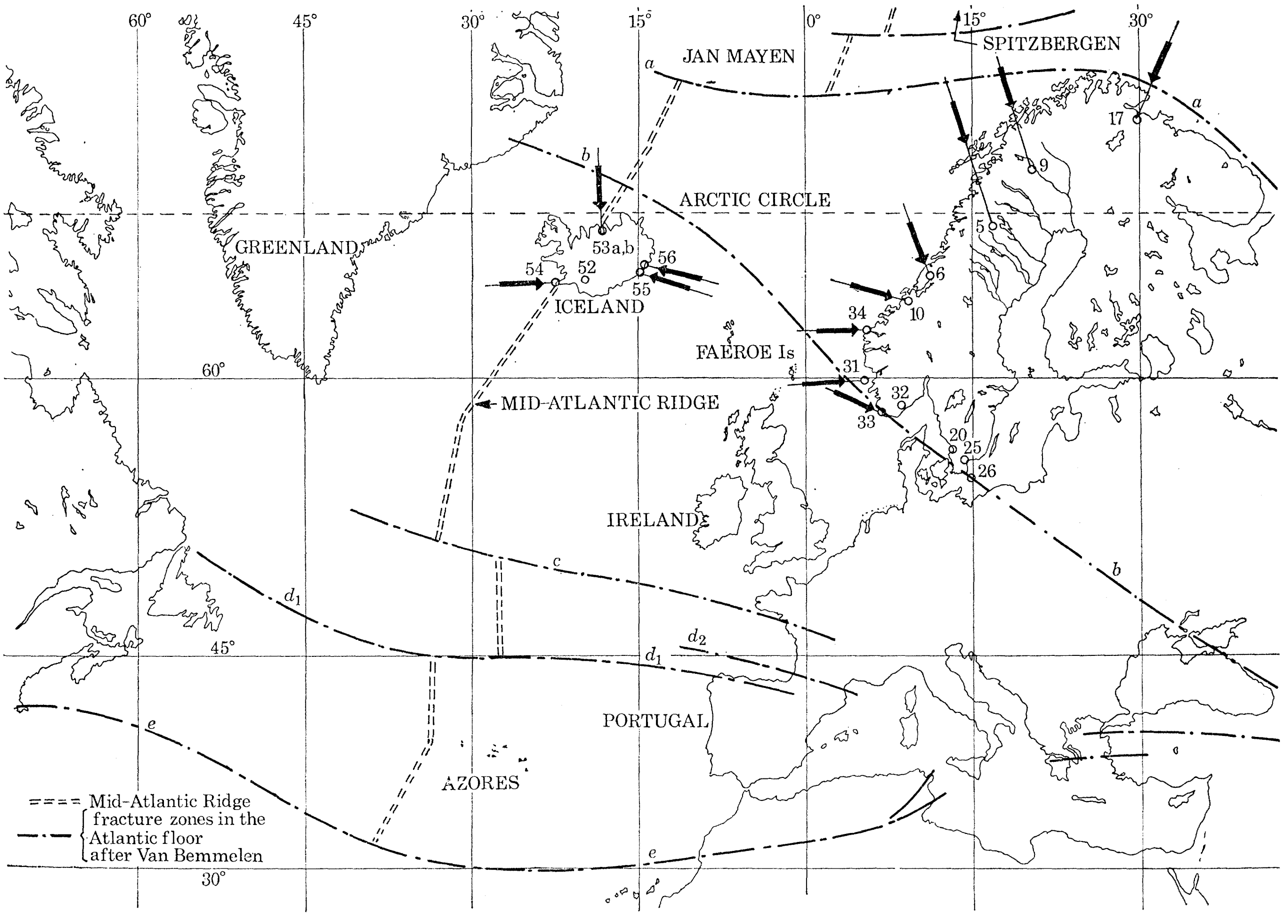


FIGURE 5. The direction of maximum horizontal compressive stress in the border zones between, on the one hand, the floors of the Atlantic Ocean and the Norwegian Sea and, on the other, Iceland and Norway (forces of reaction).

### *Horizontal compressive stresses recorded on Iceland*

The horizontal stress ellipses in figure 4 show the magnitude and direction of maximum horizontal compressive stresses in the bedrock at the measuring points. At points 52–54 $\sigma_1 + \sigma_2$ was 70 kgf/cm$^2$ at ground level; the rock here is less competent. At points 55 and 56 it is competent and the stresses are much higher, with $\sigma_1 + \sigma_2 = 212$ and 180 kgf/cm$^2$, respectively, which magnitudes correspond to the stress level in the old Fennoscandian granite area and in most parts of the world. A stress of 70 kgf/cm$^2$ in the volcanic areas of Iceland is, however, quite a high value, though less than in competent rocks. In fact, it is equal to the deadweight of 250 m of rock. Moreover, this value is the horizontal stress in the upper zone of the crust, and increases with depth.

A point of major significance is that at all points of measurements on Iceland the stress was *compressive*; nowhere was a tensile stress found.

### *Horizontal shear stresses in vertical planes through the bedrock*

The magnitude and direction of maximum horizontal shear in the bedrock at the measuring points is also shown in figure 4. At points 55 and 56 where the rock is competent, values of $\tau_{\max}$ of 27 and 45 kgf/cm$^2$, respectively, were recorded. At points 52–53*a*, *b* $\tau_{\max}$ ranged from 16 to 24 kgf/cm$^2$, values that are as much as 30 to 50 % of the value of the maximum horizontal compressive stress $\sigma_1$ at the same points. In continental areas of the Earth's crust the horizontal compressive stresses are normally several times higher than the associated shear stresses. *This means that it is a horizontal shear stress field that most seriously threatens the stability of the Earth's crust on Iceland.*

Figure 5 tells a great deal about the stress situation of Iceland. Point 54 is located in the area where, as said above, the Mid-Atlantic Ridge supposedly meets Iceland from the south and point 53 where the Ridge intersects the nothern shore. In both areas the direction of $\tau_{\max}$ coincides with the apparent direction of the Ridge.

At point 52 inland (figure 4) the directions of $\tau_{\max}$ are N 7° E, N 83° W – that is to say, they coincide with the directions of the active volcanic zones in figure 7: N 83° W with A, B, C, D, and N 7° E with D, G.

At points 55 and 56 the coast of Iceland is sheared approximately in one of the directions of maximum shear; the shear stresses are probably emanating from a field in the sea bed. The same applies to the coastline in the southwest. In northwest Iceland numerous fiords and indentations in the fiord lines follow the directions of $\tau_{\max}$ at point 53; the thin lines represent horizontal shear in these directions.

To sum up:

(1) It seems improbable that the high compressive stresses in the southeast border zone derive from the horizontal stresses of far less magnitude acting in large central areas of Iceland.

(2) Characteristic of stresses in the bedrock on Iceland is the prevailing direction of shear, with a tendency to shear the whole island right across parallel to the direction of the Mid-Atlantic Ridge and along volcanic areas approximately following it.

(3) Iceland seems to represent a hollow or depression in the enormous horizontal stress field that probably exists in the deep sea floors around the island.

(4) The Mid-Atlantic Ridge would appear to be a shear zone between the western and eastern halves of the Atlantic Ocean, and thus a site of horizontal movements between them where shear stresses are released as the Earth contracts. Volcanic activity would then occur in the area of the Ridge.

(5) According to the theories of continental drift and ocean floor spreading volcanic material is forced from below through the Mid-Atlantic Ridge, pressing the continents apart. If this were so, however, the direction of compressive stresses in the Ridge area would be perpendicular to the Ridge, but according to measurements at point 54 within the Ridge area this direction is at 45° to the Ridge; this is inconsistent with the occurrence of such movements in the sea floor and shows that the Ridge is a shear zone.

## MONT BLANC

I will conclude with some details of stress measurements performed in the Mont Blanc massif and discuss the stress condition found there. The determinations were made in the road tunnel 11.6 km long between Courmayeur in Italy and Chamonix in France.

Figure 6 shows a vertical section through the rock massif and the road tunnel. The overlying rock has a maximum thickness of 2500 m and a minimum of 1750. The tunnel cuts through homogeneous gneiss-granite for 7 km in the centre of the massif. On the French side the gneiss-granite area is bounded by a 3 km wide zone of crystalline schist, and on the Italian by 1.5 km of limestone.

If the stress conditions in this young, still active Alpine mountain range could be determined it might also be possible to study movements of the rock in the massif and thus get an insight into the way in which mountains are formed.

Measurements were made at many points in the tunnel. In fact we were working during a whole year on the project. Many difficulties had to be overcome – for instance, every precaution was taken to prevent the penetration of water if the bore-hole happened to encounter a water-bearing fissure (the water pressure could be as high as 3000 m).

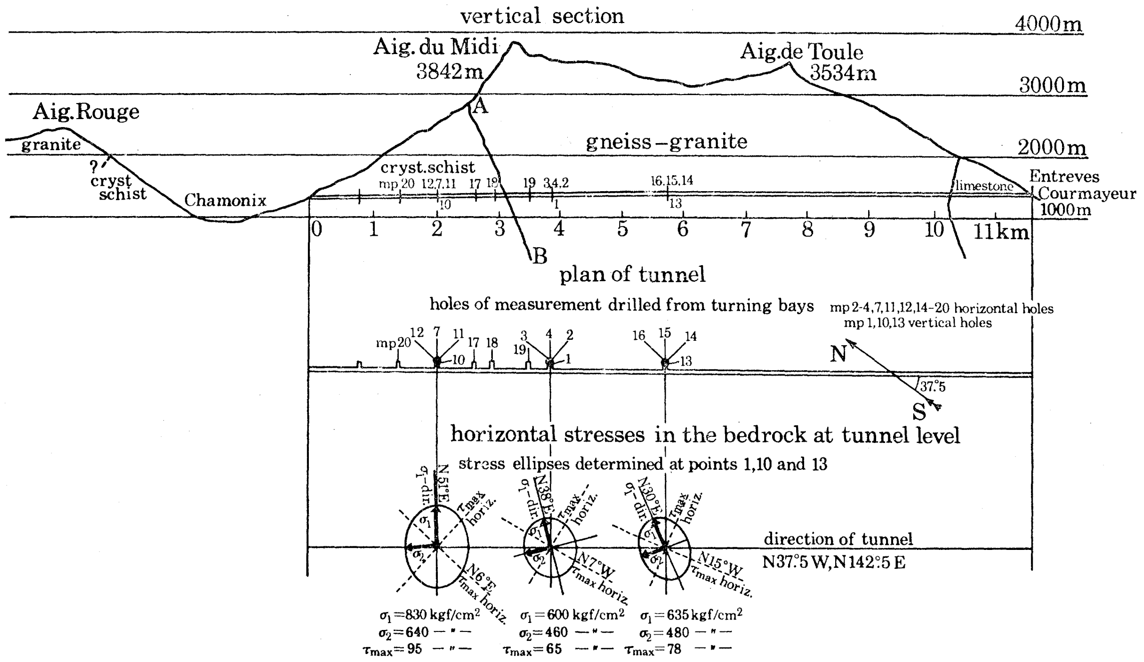


FIGURE 6. A vertical section through the Mont Blanc massif and the road tunnel between Courmayeur and Chamonix. The location of the measuring boreholes. Magnitude and direction of the horizontal stress field in the area is shown by the horizontal stress ellipses at points 10, 1 and 13. The transition zone between the crystalline schist and the gneiss-granite is marked by a line A–B.

The gneiss-granite is of precisely the same composition at the level of the tunnel and at the top of Aig. du Midi, 3842 m. It is rich in quartz and seems to have been exposed to very high horizontal compressive stresses.

The location of 16 measuring points is shown in figure 6; three were drilled vertically, seven horizontally at 90° to the direction of the tunnel and six at 45° to it. As the holes were drilled to a depth of 15 to 20 m from the end wall of turning bays, which are usually 15 m from the tunnel, the stresses were recorded so far from the tunnel cavity that its presence can have had little influence on the natural stress field in the rock at the points of stress recordings.

The figure also shows the magnitude and direction of the horizontal stress field in the bedrock at the position of vertical holes nos. 13, 1 and 10. In the gneiss-granite area the magnitude of $\sigma_1$

is about 620 kgf/cm² and of $\sigma_2$ about 470. The stresses are higher in the crystalline schist, with: $\sigma_1 = 830$ kgf/cm² and $\sigma_2 = 640$. The maximum horizontal shear in vertical planes through the bedrock at points 13, 1 and 10 is 78, 65 and 95 kgf/cm², respectively. These high values of

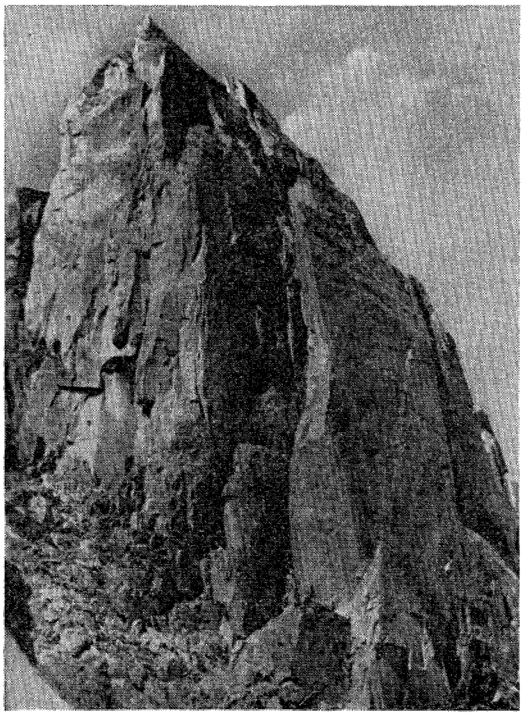
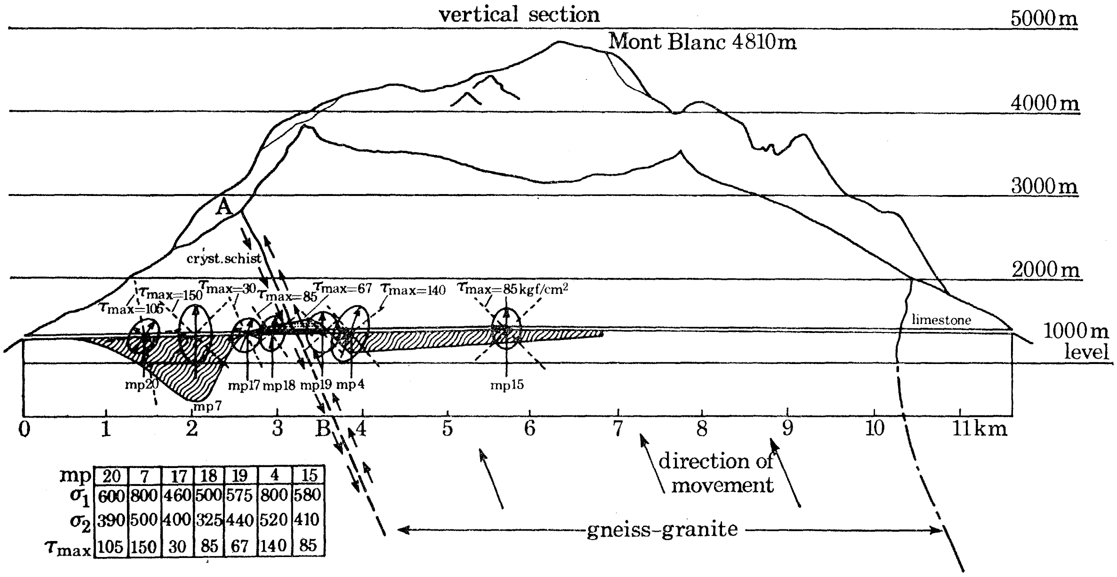


FIGURE 7. Vertical planes of fracture in the east–west and north–south direction in the Mont Blanc massif; the top of Adolfo Ray (3670 m). The directions of the planes are the directions of horizontal $\tau_{\max}$ and shear fractures found by the measurements at tunnel level.



| mp | 20 | 7 | 17 | 18 | 19 | 4 | 15 |
|---|---|---|---|---|---|---|---|
| $\sigma_1$ | 600 | 800 | 460 | 500 | 575 | 800 | 580 |
| $\sigma_2$ | 390 | 500 | 400 | 325 | 440 | 520 | 410 |
| $\tau_{\max}$ | 105 | 150 | 30 | 85 | 67 | 140 | 85 |

FIGURE 8. Vertical section through the Mont Blanc massif and the road tunnel. The ellipses demonstrate the stress distribution in the bedrock at tunnel level. The table in the figure shows the magnitudes of the stresses. High vertical shear stresses especially in the schist corner. The shaded (overpressure) and stippled (underpressure) areas show the difference between the measured vertical load and the dead weight of overlying rock calculated from the height of the mountain at the points of measurement.

$\tau_{\max}$ show that shear is the kind of stress that is responsible for the numerous vertical fracture planes in the rock massif. The horizontal directions of the planes of $\tau_{\max}$ are about N–S, E–W.

The gneiss-granite is fissured in vertical planes in the horizontal directions of $\tau_{\max}$. These fracture planes probably split the rock from very deep levels up to the top of the mountain. The top of Adolfo Bay (3670 m) (figure 7) has *vertical shear planes* forming rock faces cut in the N–S and E–W directions – that is, parallel to the direction of horizontal $\tau_{\max}$ and shear fractures disclosed by the measurements at tunnel level.

Figure 8 shows a vertical section through the massif and the tunnel. The stresses were determined in a series of points in the plane of the section – nos. 15, 4, 19, 18, 17, 7 and 20 (see also figure 6). As the measurements show, the vertical stress in the gneiss-granite exceeds the deadweight of the rock, and this 'over-pressure' varies from 160 at point 4 to 90 kgf/cm$^2$ at point 15. Around the transition zone in figure 8, where the gneiss-granite and the schist make contact there is an 'under-pressure', the recorded vertical stress being lower than the deadweight of overlying rock. The shaded area represents over-pressure and the stippled under-pressure.

In the centre of the schist area, point 7, very high vertical compressive stress is acting, but the stress in the schist, dangerous for the stability, is shear; this can be as much as 150 kgf/cm$^2$, and is thus probably close to the breaking strength of this rock. The first kilometre of the tunnel, in particular, contains dense vertical fissures, and because the risk of water penetration was too high, no measurements were performed near the ends of the tunnel. At point 20 the direction of $\tau_{\max}$ is almost vertical, and its magnitude 105 kgf/cm$^2$; at points 7, 17 and 18 the direction is more nearly parallel to the transition zone *A–B*. The shear stress is a maximum at point 7.

### *The mechanism of the movements of the gneiss-granite in the mountain*

Our measurements show that the gneiss-granite is subjected to 'overloading' from below and movements in the Mont Blanc massif. The underlying mechanism seems to be the following.

From very deep levels in the Earth's crust the whole granite area is moving upwards along the zone of contact between granite and schist (line *A–B* in figures 6 and 8), under high pressure acting from below. The vertical planes of fracture in the granite caused by the horizontal shear stress field follow the upward movement without changing their mutual horizontal position, and arrive at the top.

The crystalline schist forms the surface layer of the crust, probably 3 or 4 km thick. The valley at Chamonix seems to have been formed by erosion of the upper part of this layer. When the gneiss-granite slides along *A–B* frictional forces set up stress in the schist, and tend to retard the displacement. Especially to *the part of the schist massif below the valley side the schist will be highly stressed by the forces set up by the displacement.* Maximum shear appears in planes roughly parallel to the plane *A–B*, along which sliding seems to be taking place. *The presence of these exceptionally high shear stresses in the schist corner confirms the displacement.* As mentioned, the 'over-pressure', which probably originates far below the level of the tunnel, reflects the action of enormous vertical forces that could quite possibly initiate and continue an upward movement of the gneiss–granite in the way described.

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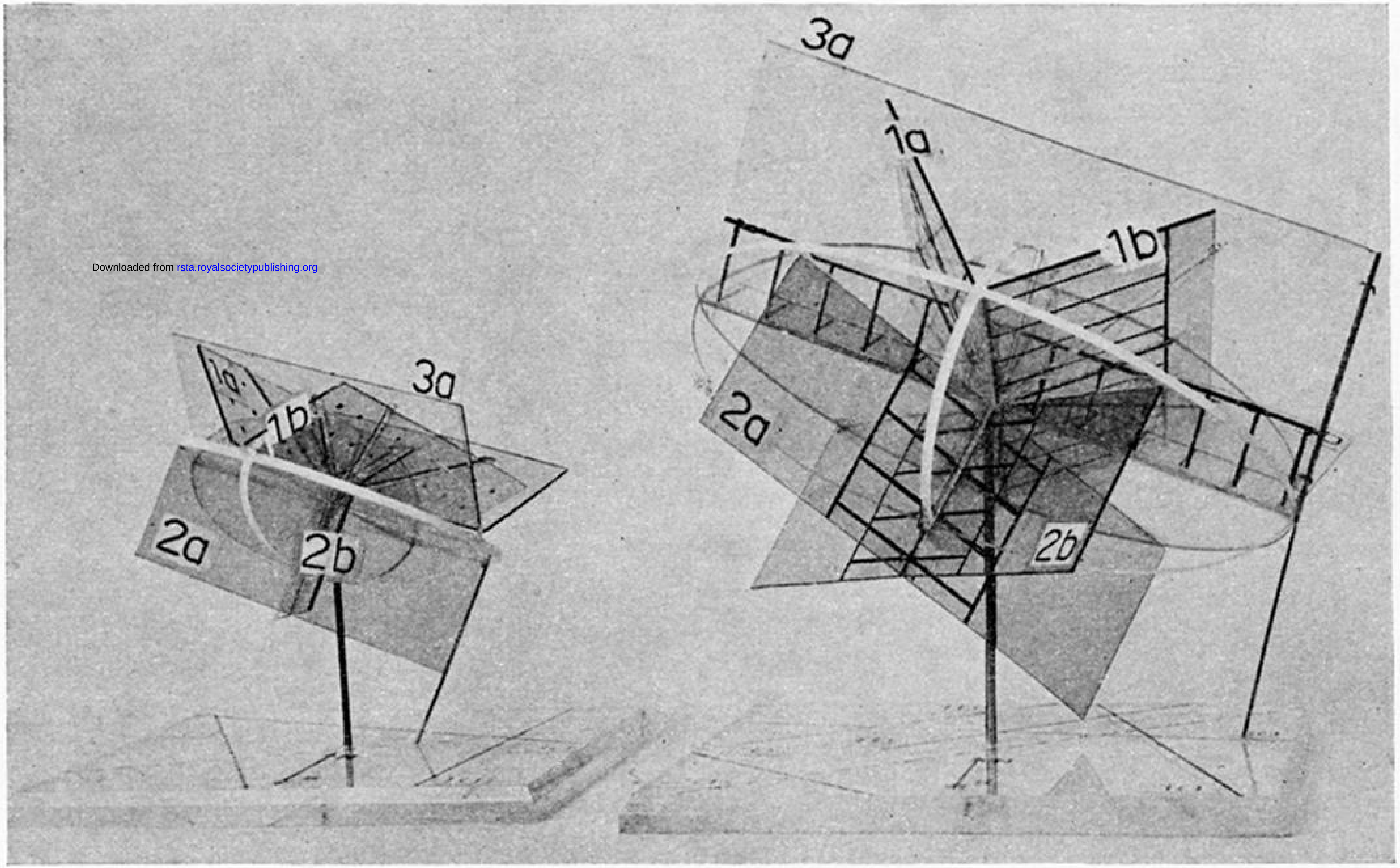

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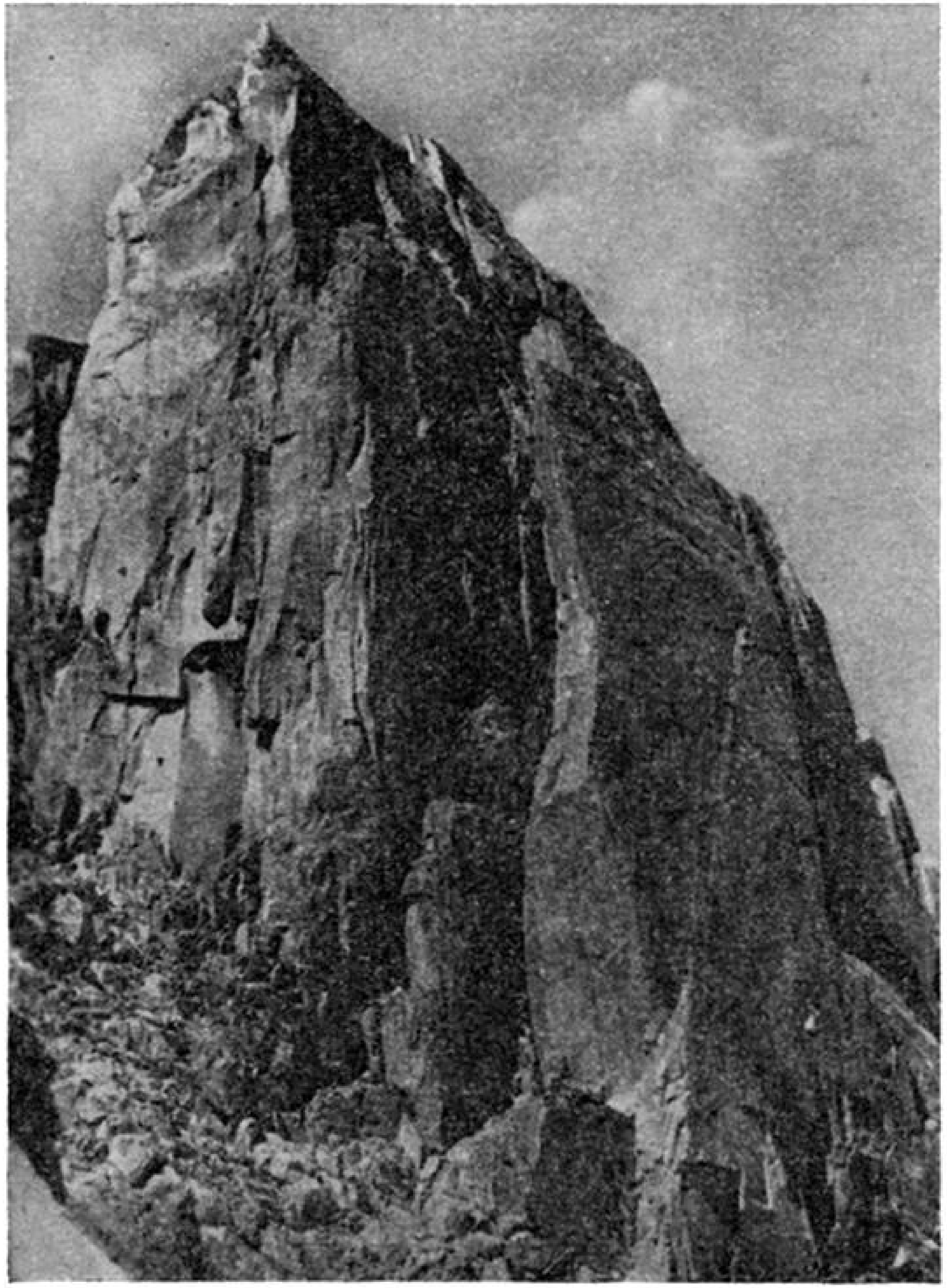

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