Institut für Geophysik der Technischen Universität Wien

Institute for Geophysics of the Technical University Vienna

RESEARCH
at the INSTITUTE OF GEOPHYSICS of the TECHNICAL UNIVERSITY OF VIENNA in the INTERNATIONAL GEODYNAMICS PROJECT

by

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With 4 Figures

1. Introduction

The Institute of Geophysics at the Technical University of Vienna was founded in the Spring of 1971. Since its inception, the Institute took part in the International Geodynamics Project. The main research effort was spent on the elucidation of the geophysical stress field and the concomitant mass motions in Austrian Alpine regions. During the summer months, regular field work was undertaken which was supplemented in the winter by in-situ stress measurements below ground. The whole research program was divided into several sub-programs which will be discussed below in detail.

2. Observations of valley closures and tectonic slope movements

Geodetic measurements of mass movements were made near Hallstatt, on the Lesach Ledge, at a slope near Wörschach and on a mountain side near Irschen. At the three locations mentioned last, markers were established and zero measurements were made.

In later years, follow-up measurements were made which were supplemented with other geophysical investigations, such as seismic studies of the ground, in order to ascertain the structure of the sliding masses. In every case, mass movements of the order of centimeters were found; the pattern of the motion fits in every case into the scheme envisaged by Terzaghi ("rotational slump"). Thus, Fig. 1 shows the results from the Lesach Ridge. The displacement vectors evidently correspond to those of a slump and are of the order of mm/year. A comparison with investigations of the neotectonic stress field shows that the mass movements are predestined by the latter and triggered by the erosion at the valley floor. The mean displacement direction coincides closely with one of the principal stress directions of the neotectonic stress field. The change in the orientation of the schistosity surfaces in the displaced masses indicates a tilting of the strata. The thickness of the layers loosened up by the mass-movements was determined by seismic experiments as of the order of 100 m.

With regard to Hallstatt, our measurements constituted a follow-up to geodetic measurements that were made in 1954 by the Bundesamt für Eich- und Vermessungswesen. It was possible to establish that large displacements (up to meters) took place in the interval. The observed displacements were also compared with measurements of the orientation of recent joint-surfaces. It could be shown that the mechanics of the motion as well as of the formation of the joints can be explained by picturing the slope as creeping plastically with the surrounding rock boundaries acting as abutments. Thus, the material of the slope is partially in an active, partially in a passive Rankine state. The joints found in a mine beneath the slope can be explained by the overburden pressure and the active flowing pressure.

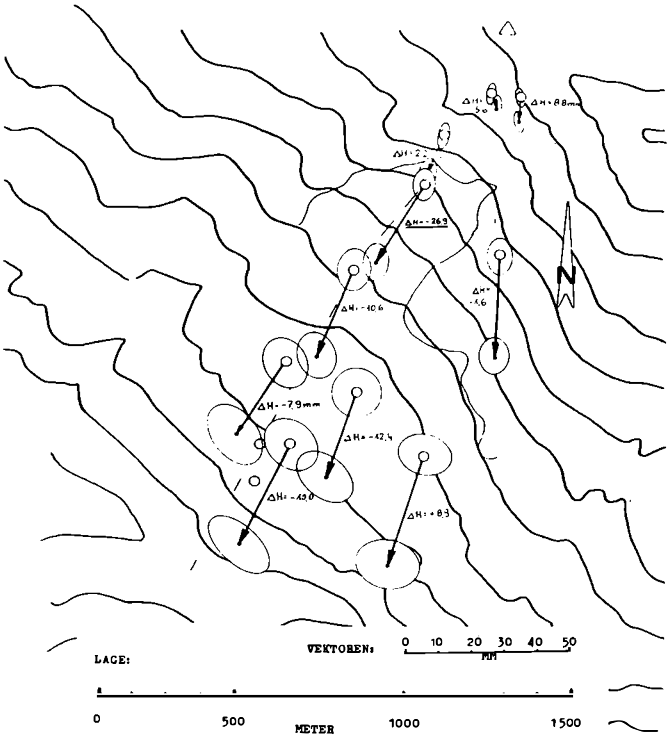

Fig. 1: Displacement vectors on the Lesach Ridge between 1973 (o) and 1976 (.) △H = significant change in altitude.

3. Investigation of the dynamics of unstable areas

Originally, this project concerned the investigation of the dynamics of scree slopes. Later, it was extended generally to creeping slopes.

Thus, topographic, morphologic and geophysical investigations of scree slopes in the Hochkönig area of Austria were made. It was found that a scree slope consists of various independent scree streams; the average inclination decreases from top (34.9°) to bottom (27.4°) over 300 m of elevation. The debris size distribution does not change over the slope (there is no increase in sizes from top to bottom). The individual sizes are distributed in stripes and tongues; this points to the fact that the buildup of the slope occurs in the form of miniature overlapping landslips. The grain size decreases with depth points to a sieving effect (small pieces fall through the holes between large ones). Seismic measurements yielded the result that there are 3 layers: a layer on top, some 15 m thick, a consolidated layer to a depth of 30 m and rock below. There is no significant variation of the depth to rock over the entire scree slope.

Exact geodetic measurements of the scree slopes in subsequent years yielded the result that the motion of such slopes takes place entirely by surficial mini-slides; there is no internal creep. This is quite contrary to what had been expected in the literature by other authors.

Investigations of grass slide phenomena at the Lesach Ledge yielded the result that the latter can be explained by a dry-frictional model. The origin of terracettes is to be sought in the slowing down of the internal creep in the slope by consolidation-phenomena.

A geomechanical investigation has been made of a slide area in the Felber Valley (Salzburg Province) in Austria. For this purpose, tachymetric, seismic, geomorphological and geological studies were carried out. It was found that slow mass movements occur from the ledge atop the valley down to the very bottom. Atop the ledge, the movements present the aspect of a "mountain fracture", in the middle of the slope, the aspect of soil-creep and at the bottom, the aspect of an actual slide. It was found that the orientation of the "mountain fractures", of the joints in the rocks bounding the slide area and of the features on the creeping slope all fit into one single geophysical stress-pattern, viz. into one with a maximum horizontal compression in the N-S and a minimum compression in the E-W direction. This fits together well with the general views on the tectonics ofthe Alps commonly found in the literature.

Similar results were obtained from an investigation of an unstable area near Bad Gastein. Many houses of this resort-town show traces of movement (cracks in walls and foundations). Data from the Bundesamt für Eich- und Vermessungswesen in Vienna were used for a determination of the displacement patterns. Support was again obtained for the conjecture that all movements are basically designed by the tectonic stress field, although the individual triggering effect must be sought in exogenetic agents.

4. Investigations of the visible effects of the geophysical stress field

Geomorphological features, joint orientations and the layout of valleys in a mountain region can often be interpreted as visible effects of the stress system that produced these phenomena. Thus, a large program was undertaken to analyse the geotectonic significante of such features.

First of all, on-the-spot geomorphological investigations were undertaken in the Hochkönig region and in the Pinzgau. Thus, it was shown that the characteristic features in mountain massifs can be classified into those that have been primarily caused by the tectonic stress field and those in which selfgravitational effects are of major importance. In this fashion, the morphology of mountain peaks can be shown to be primarily stress-induced.

Second, a thorough study of the orientations of joints not only in Austria, but in many parts of the world was undertaken. It has been known for some time that large-scale faults are caused by forces in the Earth's crust. However, it has now also been recognized that the innumerable small joints seen everywhere in outcrops are the direct outcome of neotectonic stresses. The phenomenological evidence has recently been summarized by Scheidegger [43] as follows:

a) At a single outcrop, one finds ordinarily three joint systems which are usually very definite: One system is near-horizontal (dips 0° to 40°) and corresponds to some lithological factor; the other two systems are near-vertical and almost orthogonal to each other (angle of intersection 80°—90°).

b) The non-lithological joints in fresh outcrops appear to cut clear across joint systems of obviously older age. These joints are therefore to be interpreted as "tectonic" joints.

c) Several outcrops near to each other (within a few kilometers) usually show preferential joint orientations that are consistent with each other.

d) Outcrops within a region (10—20 km radius) commonly show, if treated together, definite preferential "tectonic" joint orientations. When the outcrops are considered singly, however, one often finds that about 1/5 of them show "anomalous" tectonic joint orientations which are rotated up to about 30° with regard to the "regionally" preferential orientations. The "anomalous" outcrops are not randomized, but show a consistency amongst each other.

e) The well-developed regional joint system can commonly be explained in terms of the neotectonic stress system if the bisectrices of the regional joint strikes are taken as principal horizontal tectonic stress directions. It has generally been assumed that the tectonic joints (as defined above) are Mohr type fracture surfaces, but the commonly observed large angles between conjugate joint sets may, in fact, indicate that the fracture is not of the Mohr- type at all. The joint sets align themselves very closely with the planes of maximum shear in the tectonic stress field which may indicate that they are the result of some ductile or plastic slippage process. Thus, an obvious phenomenological explanation of joints would be that they are the response to an instantaneous creep process induced in the horizontal plane by the momentarily acting tectonic stresses.

On the basis of the above remarks, it is possible to deduce the orientation of the principal tectonic stress directions from a measurement of joint orientations. In the case of Mohr-type fracture, the bisectrix of the smaller angle should be the greatest compression. However, inasmuch as, as noted, the angle between steeply dipping conjugate joint sets is usually close to 90°, it is often not possible to distinguish reliably between the largest and smallest principal stress direction.

The determination of the preferred joint orientations in an area has to be carried out by a statistical procedure. For this purpose, a computational method was developed by Kohlbeck and Scheidegger [26]. In that method, two statistical probability distributions of the type $\exp(k \cos^2 d)$ about a mean direction are fitted to the data; the two best-fitting mean directions are determined by computer using a function-minimization procedure. The computational procedure is nothing but a development of the older method of drawing density-diagrams for the joint-directions in some suitable projection of a unit sphere and picking two density maxima. From the position of the two density maxima, the principal stress directions can then be calculated. If the angle between conjugate sets is substantially different from 90°, it is even possible to identify which is the largest (P) and which is the smallest (T) compression direction. For visualization, it is often convenient to also give the corresponding joint-density diagrams. As noted, the above idea has been applied world-wide to the determination of the orientation of the principal stress directions of the stress field causing the joints. It was found, world-wide, that the principal stress directions determined in this fashion agree with those that one would expect from present-day plate tectonics. As an example, Fig. 2 shows the principal stress directions found for the northern rim of the Mediterranean. This implies the perhaps somewhat startling inference that the vast majority of visible surface joints are of very recent origin. However, when one considers the fact that in most tectonically active areas of the world vertical motion rates of mm/year (= km/million years) are prevalent, the idea that surface joints are very new indeed, is perhaps no longer so surprising.

The above idea was further extended to the hypothesis that even valley trends might be pre-designed by the geotectonic stress field. The assumption that valley trends are predetermined by geotectonic phenomena stands in contrast to the assumption of valleys being solely caused by exogenic agents (i. e. wind, water and ice). In fact, there is a certain controversy about this matter to this day, but the evidence in favor of some geotectonic control of the valley orientations is building up steadily. Thus, it has been shown that the main characteristic of exogenic agents is their randomness [15]. Valleys caused by erosion alone should, therefore, be randomly oriented. Evidence from statistical analysis of valley directions shows that the latter are not random (see below). Furthermore, the often large vertical displacement rates in mountain areas suggest that the surface features are of very recent origin. This makes it difficult to believe that modern river-nets should have been determined by some ancient drainage pattern which is retained to this day.

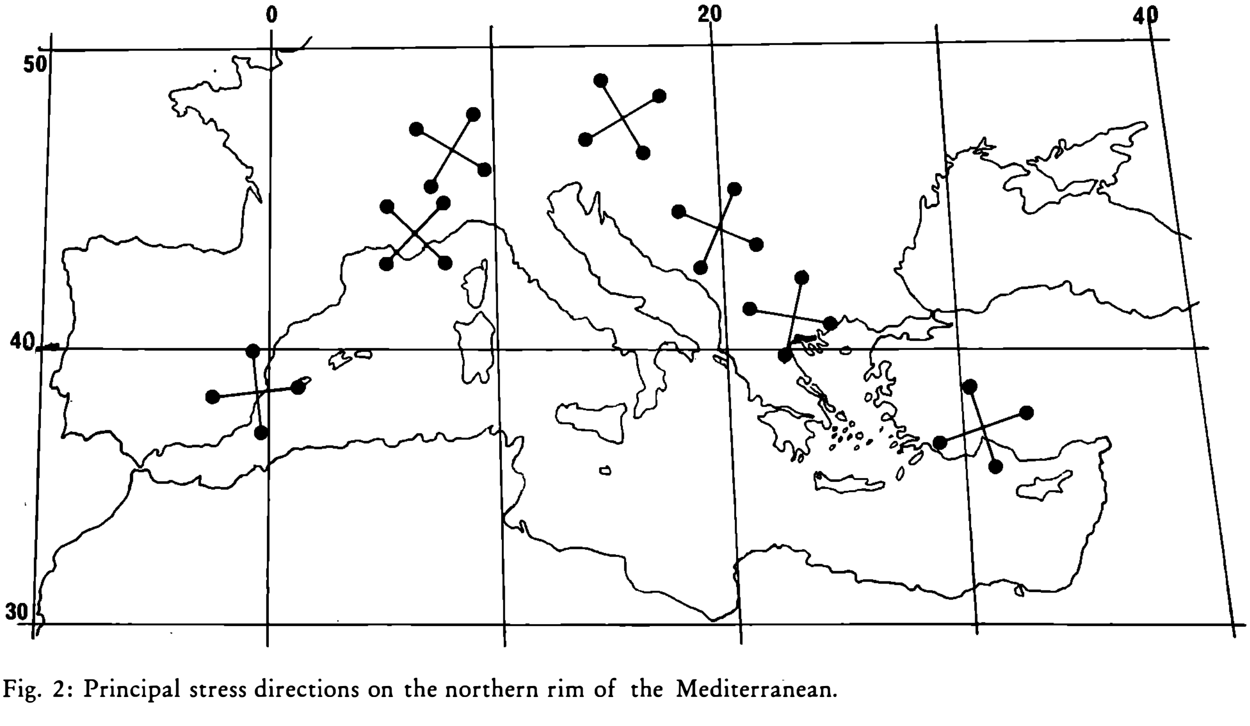

Fig. 2: Principal stress directions on the northern rim of the Mediterranean.

In order to study their orientations, the valley directions have to be "rectified" (i. e. straightened) by considering them as edges in a graph. This may be a somewhat "brutal" procedure, but it is at least independent of the bias of the researcher. Otherwise, the fitting of straight (and therefore measurable) segments to the "wiggly line" representing the river course on a map, would be extremely arbitrary. However, in the described fashion, the distribution of valley orientations can be represented numerically. By considering valley trends so to speak, as "vertical joints", and by calculating the preferred orientations of the latter in an area, it was found in the Alps (Switzerland and Austria) that the preferred valley trends do indeed correspond to the preferred orientations of the surface joints, and thus, that they are primarily induced by the neotectonic stress field.

5. In situ stress measurements

Measurements of stress in situ were made by the so-called doorstopper method below ground in the copper mine at Mitterberg, in a drive of a tungsten mine in the Felber valley, in a highway-tunnel through the Gleinalm, in a lead-mine near Bleiberg, in a coal-mine near Fohnsdorf, as well as at the surface in the Ebriach gorge. In all cases, the so-called "doorstopper" (stress relief) method has been applied.

The copper mine at Mitterberg underlies the Hochkönig Massif which is formed by a Triassic calcareous block lying above softer Paleozoic layers. Three holes were drilled from a drive 750 m below the surface so that, in principle, the complete stress tensor could be determined. It was found that the absolute stress values obtained were not significant. However, it could be established that the direction of the maximum pressure is downwards from NNW (upward from SSE) with a plunge of 70° towards the horizontal. The stresses normal to that direction have a value of about three quarters of the maximum pressure. It appears that the presently acting stresses are caused entirely by the overburden inasmuch as the maximum pressure direction points exactly towards the summit of the Hochkönig. In the directions normal thereto, a stress relief occurs in the relatively soft Paleozoic layers.

For the stress measurements in the tungsten mine of the Felber valley the point of the measurements was located in the lower slate-cover of the Tauern Window of the Austrian Alps. Three holes were drilled in different directions for the complete determination of the stress tensor. The elastic properties of the rock were investigated by various methods. The most important result was the determination of the orientation and value of the maximum principal compression. It turned out that there is no indication of a tectonic modification of self-gravitational stresses.

The location in the Ebriach gorge was in the vicinity of the Periadriatic Lineament in a small diabase dyke which is bounded on both sides by slates of much smaller rigidity. For the principal stresses, values of $\sigma_1 = 2$, $\sigma_2 = 6$ and $\sigma_3 = 9$ MPa were found. σ_3 has an inclination of 30° towards the vertical and corresponds to the action of the superjacent rock masses. σ_2 and σ_3 are approximately horizontal. The direction of σ_3 is NNW. However, in view of the closeness of the values of σ_2 and σ_3, one can hardly speak of a preferred orientation.

The average values of the horizontal and vertical stresses are in the ratio of 2:1. This ratio is in conformity with those found on a world-wide basis near the surface of the Earth.

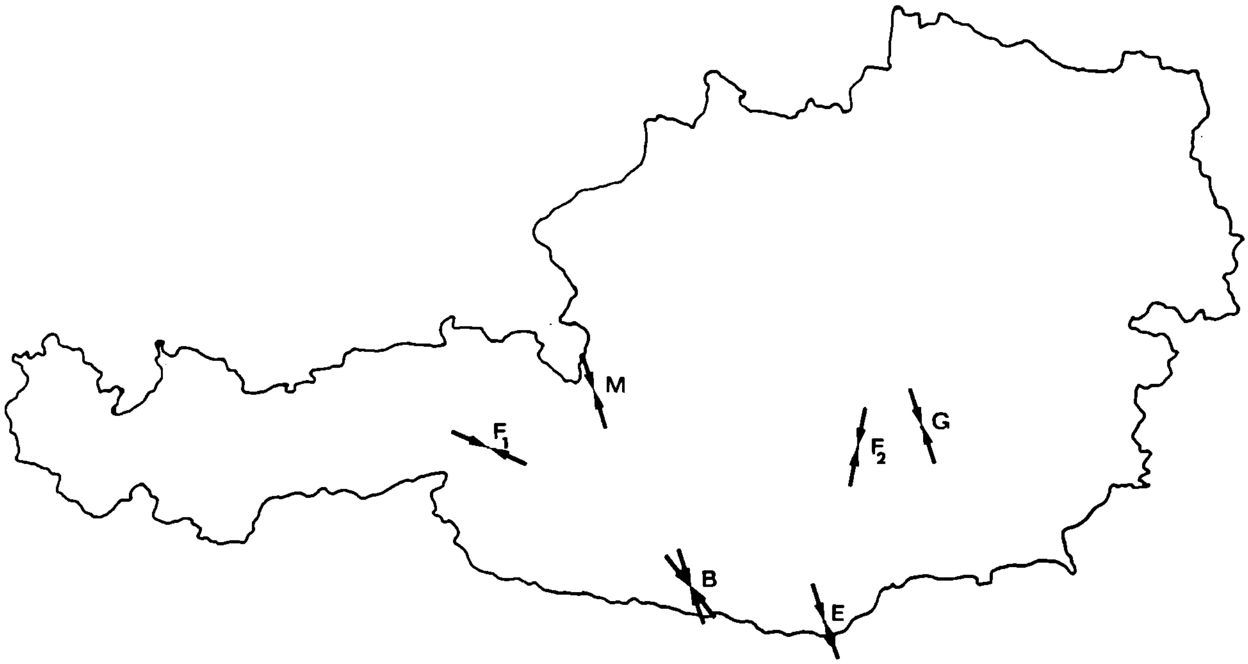

Fig. 3: Horizontal projection of the maximum compression directions obtained by in-situ stress measurements in Austria. B: Bleiberg, E: Ebriachklamm, F_1: Felber Valley, F_2: Fohnsdorf, G: Gleinalm-Tunnel, M: Mitterberg.

In situ stress measurements have been carried out in the Alpine basin of Fohnsdorf not only with CSIR doorstoppers but also with triaxial cell equipment. The site was situated within sandstone at 414 m below sea level at a depth of 1100 m. The modulus of elasticity, Poisson's ratio, the density and the strength of the sandstone have been evaluated. The measurements yielded a stress tensor with greatest stress of about 40 MPa **in NS** direction and lowest stress of 10 MPa in E-W-direction. The intermediate principal stress is vertical and corresponds to the weight of the overburden.

Thus, an indication of the neotectonic stresses was obtained at some keypoints in Austria. The procedures are very expensive and also scatter somewhat; they generally show that the directions of the principal stresses agree with those expected from plate tectonic theory as modified by the gravitational effects of the surrounding topography. Fig. 3 summarizes the results obtained.

The measured stress-values were compared with finite-element calculations of models of the surrounding areas. For the Hochkönig massif, a two-dimensional calculation was made by using the real elastic properties and the real rock densities. It turned out that the calculated stresses agreed with the observed ones, which confirms the hypothesis that the measured stresses are essentially self-gravitationally induced.

In the case of the Felber Valley, theoretical calculations of the stresses by means of a finite-element model show that the experimentally found values can be explained by the weight of the material alone as a consequence of the local topographic conditions. An essential assumption herein is that the mountain range rests on a plastic substratum so that approximately the same pressure is acting everywhere along the horizontal basis. If the mountain mass rests on a (vertically) rigid material, then the experimental stress values cannot be reproduced by the calculations. Thus, one has an indication that the rheological state of the material in the earth's crust is plastic (over geological time-ranges) already at comparatively shallow depths.

6. The Diendorf Fault

In the vicinity of Vienna, at the Eastern boundary of the Bohemian massif, there is a very pronounced fault (the Diendorf Fault) which presents itself, on account of its easy accessibility and nearness to the Institute, for study as a convenient example of a geodynamic type-feature. The fault is directly visible morphologically and is evidently also responsible for damage to buildings in various villages (Fig. 4). For its study, gravimetric, seismic and geotectonic investigations have been made.

Data on seismic intensities indicate a zone of decreased density along the fault. The shape, size and depth of the anomalous low-density mass has been calculated upon the basis of an extensive gravimetric survey of the region. By making a fit of the gravity anomalies on the two sides of the fault it is shown that the shift of the two sides has been 40 km. Magnetic investigations corroborate the gravity-results and indicate a further strong anomaly in the area around the town of Theras.

Furthermore, measurements of the orientations of joints were made. The preferred strike directions of 10 groups of outcrops in the vicinity of the Diendorf-Fault were determined; they show a basic parallelity, except for a deviation by about 30° at the entrance of the Wachau in the direction of the break-through of the Danube. The principal stress directions calculated from the joints form an essentially E-W and N-S system for the whole region.

A documentation of damage to buildings in built-up areas and of consolidationphenomena in the free field indicates a zone of tectonic activity along a line in the vicinity of the Diendorf Fault which can be related to the latter.

Fig. 4: Damaged building on the Diendorf Fault (in the village of Platt)

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