Recent crustal uplift and the present stress field of the Alps along the Swiss geotraverse Basel-Chiasso

Autor(en): **Neugebauer, Horst J. / Brötz, Rolf / Rybach, Ladislaus**

Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **73 (1980)**

Heft 2: **Symposium alpine geotraverses with special emphasis on the Basel-Chiasso profile : Lausanne, 4-5 October 1979**

PDF erstellt am: **28.04.2024**

Persistenter Link: https://doi.org/10.5169/seals-164968

Nutzungsbedingungen

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

Haftungsausschluss

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

http://www.e-periodica.ch

Eclogae geol. Helv.	Vol. 73/2	Pages 489-500	7 figures in the text	Basle, July 1980

Recent crustal uplift and the present stress field of the Alps along the Swiss Geotraverse Basel-Chiasso[1])

By HORST J. NEUGEBAUER[2]), ROLF BRÖTZ[3]) and LADISLAUS RYBACH[4])

ABSTRACT

Recent crustal movements and the crustal stress field of the Alps raise the question about the origin of these phenomena. In principle, the crustal uplift can be seen as the effect of a possible isostatic readjustment and/or of upbulging of the crust in response to the compression caused by the push of the African plate.

The corresponding forces acting on the crust have to be added to the structural forces due to the topographic loads at the mountains and to the buoyancy at the associated root zone. These three contributions to the present stress field at the Swiss Alps are discussed according to their relative effect on the recent crustal uplift and the total alpine stress field.

For this purpose a finite element model was applied to the structure of the Swiss Geotraverse Basel-Chiasso. The numerical model is two-dimensional, plain strain and allows deformation by linear and nonlinear creep. The numerical results suggest that the recent crustal uplift can sufficiently be explained by an isostatic anomaly which is interpreted as an undercompensation of the crust. The role of horizontal crustal compression and upbulging seems to be of little importance for the cause of uplift. From the numerical results and the characteristics of the stress field the overall horizontal compression acting on the alpine crust is proposed to be equivalent to < 10 MPa (100 bar).

ZUSAMMENFASSUNG

Beobachtungen zum tektonischen Spannungsfeld und zu den rezenten Krustenbewegungen der Alpen geben Hinweise auf die Dynamik der ablaufenden tektonischen Prozesse. Die Frage über die möglichen Ursachen lässt sich generell in zwei Kategorien aufteilen. Einmal direkte, d.h. vertikal wirkende Ursachen, zum anderen horizontale Ursachen.

Um die möglichen Grössenordnungen und den jeweiligen Anteil der Ursachen der rezenten Hebungen abzuschätzen, führte man numerische Experimente anhand von «finite-element»-Modellen einer zweidimensionalen Näherung der Krustenstruktur der Geotraverse Basel-Chiasso durch. Die Resultate der Rechnungen ergeben starke Hinweise, dass die negative isostatische Anomalie in Verbindung mit einem Airy-Heiskanen-Modell der Kruste zur Erklärung der rezenten Hebungen ausreicht. Weiterhin ergeben die berechneten Spannungsfelder im Vergleich mit den Daten Hinweise auf eine wahrscheinliche Druckspannung in horizontaler Richtung von etwa 10 MPa (100 bar).

---

[1]) Contribution No. 284, Institute of Geophysics, ETH Zürich.

[2]) Institut für Geophysik, TU Clausthal, D-3392 Clausthal-Zellerfeld (BRD).

[3]) Institut für Meteorologie und Geophysik, J.-W.-Goethe-Universität, D-6000 Frankfurt am Main (BRD).

[4]) Institut für Geophysik, ETH-Hönggerberg, CH-8093 Zürich (Switzerland).

1. Introduction

Recent crustal movements as well as seismicity in the Swiss Alps point towards a continuous tectonic activity. Both phenomena raise the questions about the origin of the present stress field, the system of forces which is likely to control the observed crustal movements and finally after the possible interrelation of the two sources.

Each force system responsible for either one of the phenomena or for both can be treated in terms of a composition of vertically and/or horizontally acting components.

This view finds correspondence in tectonic terms as well. In the case of the Alps we have to consider possible horizontal compressive forces due to a push of the African plate. On the other hand there is loading of the crust by the topography of the Alps with associated buoyancy forces due to the concept of isostasy ("structural" effect). In particular, KAHLE & KLINGELÉ (1979) have outlined that isostatic equilibrium does not exist for parts of Switzerland, a fact which is expressed by a negative isostatic anomaly reaching maximum values of about -30 mgal near Chur. This implies an excess of buoyancy forces beside the balanced isostatic forces.

In the context of this composite force system the recent crustal movements might be understood as a result of isostatic rebound as well as of a upbulging due to horizontal compression.

The stress field itself has therefore to be seen as the superposition of structural and tectonic stresses where the tectonic contribution might be dominated by the isostatic rebound and/or by possible horizontal compression.

In order to study the question of predominance of vertical or horizontal forces quantitatively for both, crustal uplift and the Alpine stress field, we applied a two-dimensional, plain strain numerical model. The model structure is designed to correspond to the well investigated Swiss Geotraverse across the Alps from Basel to Chiasso (RYBACH 1979).

In particular we adopted the crustal structure by a finite element model assuming linear and nonlinear flow laws. Thus, we modelled the structural stresses in response to isostatic conditions. From these stresses and the provided deformation mechanisms the influence of horizontal compression as well as that of the exceeding buoyancy forces on the stress field itself and their effect on the modelled crustal uplift can be estimated.

The numerical results in itself and in comparison with the available data support the view, that the present stress field is governed by the structural contribution while the introduced additional vertical and horizontal forces modify the character of the stress field substantially (NEUGEBAUER & BRÖTZ 1980). It will be demonstrated by means of the numerical results that the crustal uplift is probably caused by the excess buoyancy forces due to a negative isostatic anomaly. The influence of horizontal compression on the modelled uplift rates plays a minor role.

2. Observations

In the following, these observations will be reviewed which either concern the setting of our numerical model or may serve as boundary conditions for the numerical calculations.

The crustal structure along the Swiss Geotraverse is fairly well known (MÜLLER et al. 1976; KAHLE et al. 1976). Thereafter the crust-mantle boundary dips gently from a depth of about 30 km at Basel to its maximum depth near Biasca of more than 50 km. Further south the crust-mantle boundary rises steeply to a lower level of about 35 km. KAHLE et al. (1976) have shown, that for the section Luzern-Biasca of the traverse a negative isostatic anomaly (−20 mgal) exists. Figure 1*B* represents the adopted spatial distribution of crustal densities after MÜLLER et al. (1977). For the subsequent numerical models we consider the negative isostatic anomaly of the Alps between Luzern and Biasca instead of assuming compensation in part at greater than crustal depth. The traverse crosses two major crustal faults, the Rhine-Rhone line at the Gotthard massif and the Insubric line further south. The rates of crustal uplift after GUBLER (1976), shown in Figure 1*A* do not exhibit any remarkable offset in the rates there. It should be emphasized, that the maximum rates of uplift do not coincide with the maximum height of the mountain relief.

The present stress field of the Swiss Alps as revealed by studies of focal mechanisms of earthquakes is governed by compression with mainly horizontal orientation of *P*- and *T*-axes (PAVONI 1976). The derived orientation of maximum principal stresses coincides with the strike of the traverse. The focal depths vary between 5 and 15 km.

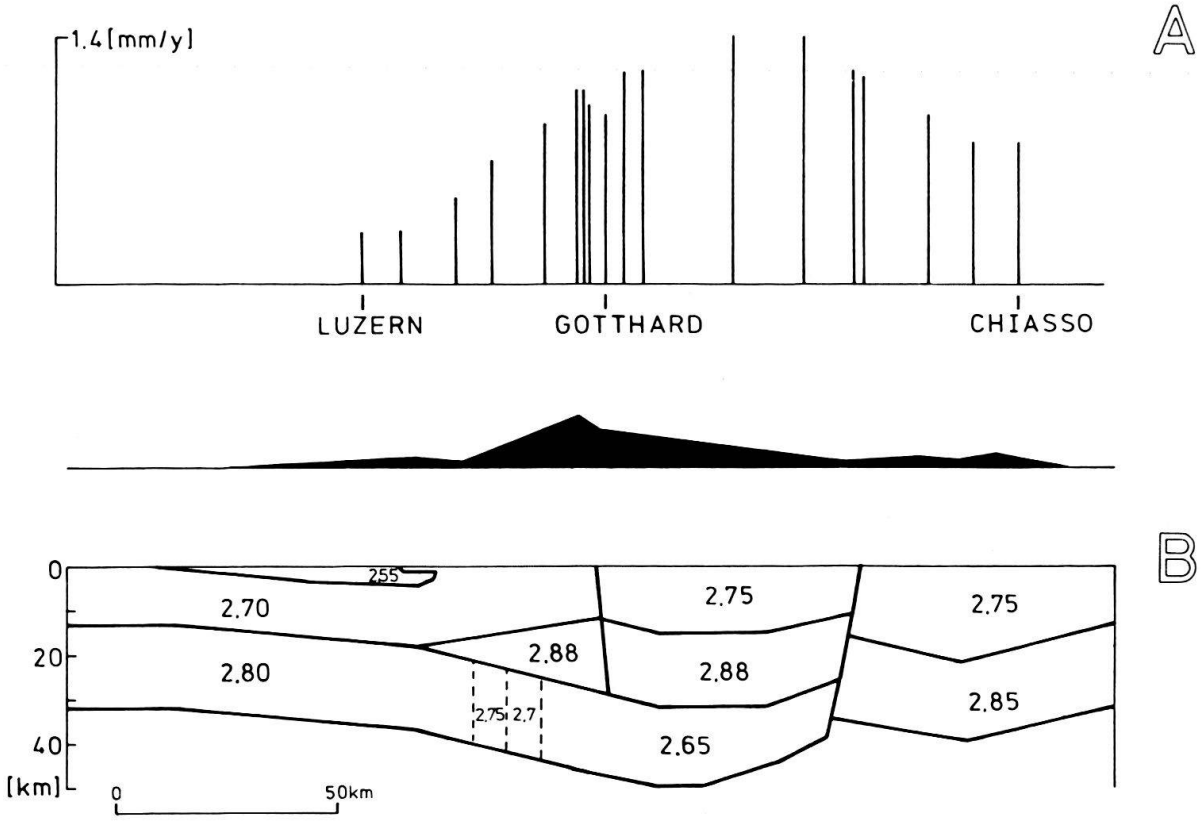

Fig. 1. *A:* Distribution of recent crustal uplift along the Geotraverse Basel-Chiasso after GUBLER (1976). *B:* Structural and density pattern (g/cm³) of the crust taken along the Geotraverse after MÜLLER et al. (1977). The corresponding mountain relief is shown in between, vertical exaggeration 2.7 times (the same applies to Fig. 2-6).

Strain release measurements shown by GREINER & ILLIES (1977) on the other hand point towards an increase of excess of horizontal compressive stresses from 1-2.5 MPa for the northern foreland to about 25 MPa at the Lepontine area. Despite of the few stress data MÜLLER et al. (1976) demonstrated the spatial coincidence of the maximum of crustal uplift and the maximum of horizontal stresses.

As far as seismicity can be understood as an indicator of the present stress field in the frame of existing tectonic systems the zone between Luzern and the Gotthard massif marks an outstanding area. PAVONI (1977) interpreted the relatively high seismicity in terms of a Cenozoic tectonic hinge zone between the Alps and the Molasse foredeep.

The mentioned phenomena demonstrate that characteristic features of the stress field and the observed crustal uplift are possibly related to each other. However, this problem and the origin of crustal uplift require a dynamical approach.

3. The numerical model

In order to establish an appropriate finite element model for the discussed problems we adopted the crustal structure at the Swiss Geotraverse by a three-layer model with a refinement to six layers at the alpine part of the structure. With a length of the model of 380 km we extended it with respect to the traverse further to the south (to the right). The model depth was taken 280 km; this is mainly based on the requirement for proper boundary conditions at the lower boundary. In addition to the crustal subdivision the two faults, the Rhine-Rhone line (left) and the Insubric line (right) have been approximated structurally by corresponding steeply dipping zones as indicated by dashed lines in Figure 2. The smallest element size was used for the crust with 2 km side length while the largest occur in the upper mantle portion with 60 km.

The rheology of the model structure is based on constitutive equations for diffusional flow and for power law creep according to the range of shear stress which has been calculated elastically to reach only a few tenth of MPa (ASHBY & VERRALL 1977). The transition between the two mechanisms with respect to the stress was

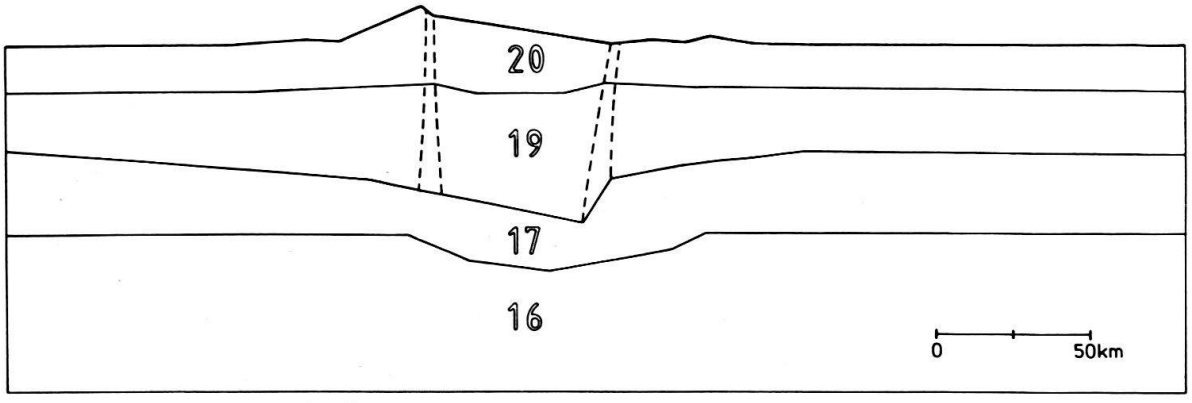

Fig. 2. Structural scheme of the numerical model. Only the upper part is shown. For further explanations see text.

chosen at 0.1 MPa (STOCKER & ASHBY 1973). The rheological subdivision is expressed comprehensively by the negative power index of the minimum strain rate per second at 0.1 MPa shear stress in Figure 2 (e.g. 19 stands for $\dot{\varepsilon} = 10^{-19}$ s^{-1}). For shear stresses above 0.1 MPa the rate changes as a function of shear stress with a power index $n = 3$ (see also NEUGEBAUER et al. 1976). The rheology is mathematically represented by the finite element displacement approach using the initial strain procedure to describe nonlinear and time-dependent behaviour (ZIENKIEWICZ 1977). The chosen technique yields the state of stress corresponding to the steady state rate of structural deformations for a simple load case. This procedure requires a minimum number of iterative solutions for each load case until steady state rates are reached.

According to the discussed principal aspects of force systems responsible for the Alpine stress field and crustal uplift we distinguish two systems of forces with corresponding boundary conditions.

The *vertical* forces are composed of the topographic loads of the Alps along the traverse ("structural" forces). These loads are balanced by buoyancy forces based on the Airy-Heiskanen type density distribution for the Alpine crust, shown in Figure 1*B*. Instead of the total amount of body forces we considered only body forces associated with density anomalies relative to a homogeneous two layer crust with constant thickness and densities ($\rho_1 = 2.7$ g/cm^3 from 0 to 13 km and $\rho_2 = 2.8$ g/cm^3 from 13 to 32 km). Thus the Airy-Heiskanen model in Figure 1*B* provides buoyancy forces due to the essential alpine root and, in addition, body forces of different sign within the main crustal layer. Thereafter the mentioned isostatic undercompensation of the Alps expressed by the negative anomaly is incorporated into the vertical force system. Constrained displacements at both ends of the crustal structure provide appropriate boundary conditions for this case. For reference reasons we modelled an isostatically compensated Airy model in the same manner.

The *horizontal* loading of the crust is introduced as a horizontal force system compressing the crustal structure from the right (= south). The forces will be represented by the numerical values of the equivalent constant compressive stress across the right end of the crustal model. Hence, horizontal loading requires the left end of the crustal structure to be fixed and the vertical displacement of the right end to be subpressed. In the following numerical calculations the two force systems will be superimposed with changeable predominance of one or the other.

4. Modelled uplift

The principal character of the deformation of the model structure is demonstrated by the orientation of the steady state deformation rates shown for different force models at selected nodal points in Figure 3. All models exhibit upward oriented deformations of the crustal structure in response to the excess buoyance associated with the negative isostatic anomaly. Case *B* shows the pattern for fixed ends of the crustal section. Here the rate orientation is dominated by the vertical direction and shows a symmetrical pattern. For a constant horizontal compression of 10 MPa (100 bar), case *A*, the horizontal component of deformation rate shows an increasing tendency towards the right. This is in accord with the view of the decay of a struc-

tural thickening of the crust due to the corresponding gravitational potential. The opposite, thrust character in the orientation of the rate with large horizontal component to the left, can be recognized in case *C*. Here we have a compressive boundary stress at the right end of the model of 60 MPa (600 bar). From the patterns shown one can find that the fixed boundary model *B* links the two others. This can also be confirmed by the reaction forces at the fixed boundary points. These forces thus correspond to a constant horizontal compression of about 25 MPa (250 bar). So the fixed boundary model *B* can be placed into the sequence of horizontal compression models. Anticipating the results of modelled stresses it should be notified that the modelled deformations are based on strain rates ($\dot{\varepsilon}$) of [10^{-15} to 10^{-13}]s^{-1} for the upper crust, [10^{-14} to 10^{-12}] s^{-1} for the lower crust and [10^{-13} to 10^{-11}] s^{-1} beneath the crust. This is the result of model generated maximum shear stresses. In this context, the strain rates modified by shear stresses yield modelled uplift rates in the same order (mm/a) as the observations.

In Figure 4*A* the modelled uplift for fixed boundaries (case *B* of Figure 3) is compared to the observations along the traverse as reported by GUBLER (1976). The observed uplift data are computed from first order levelling and are given with

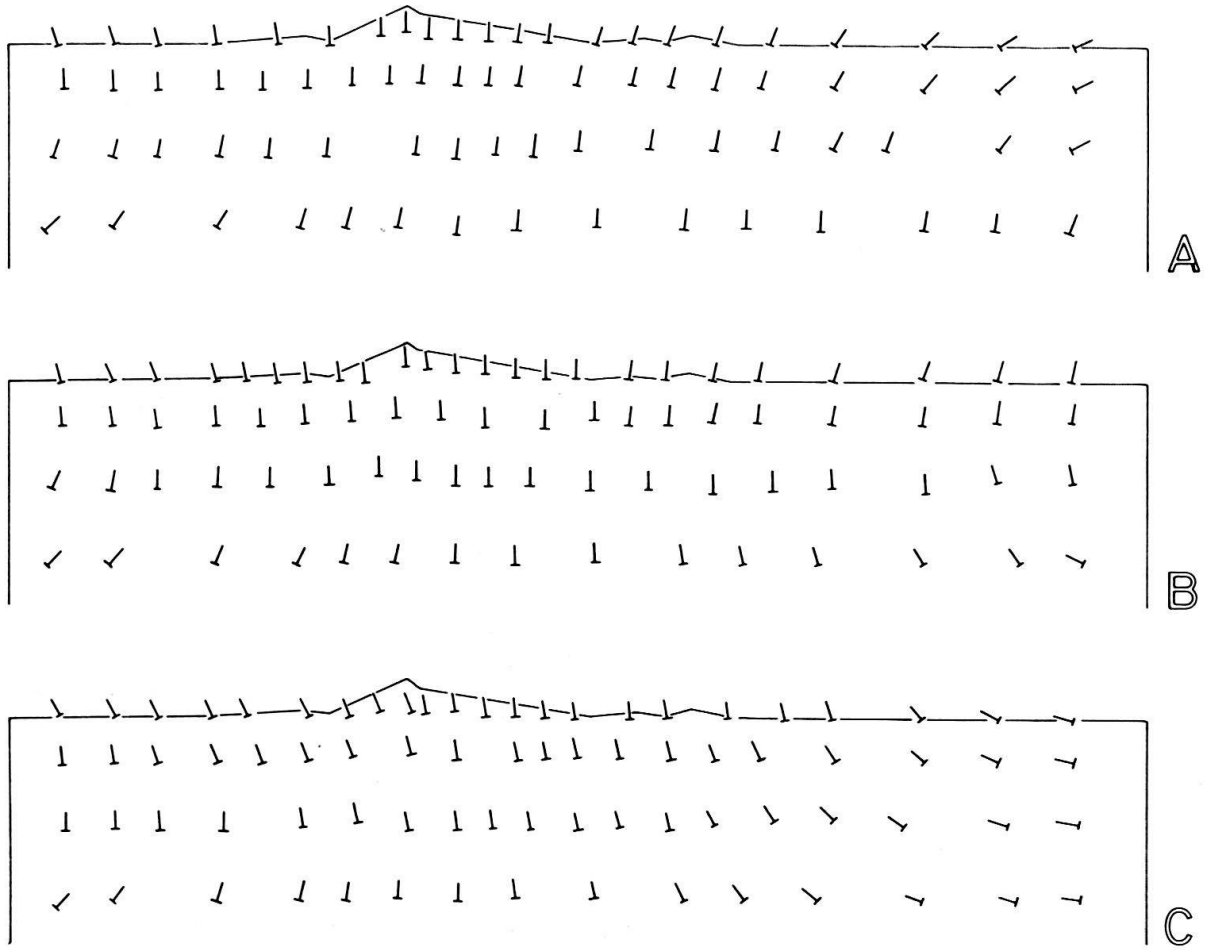

Fig. 3. Orientation of the modelled deformation rates for the top section of the model. All models are loaded by the force system due to the Airy-Heiskanen model of the crust. Additional horizontal compression: *A:* 10 MPa, *B:* 25 MPa (fixed boundary), *C:* 60 MPa.

double standard deviations of yearly elevation changes. An outstanding feature in Figure 4*A* is the coincidence of the modelled uplift rate maximum with the observations. Although the strain rates for the central alpine section of the structure are two orders of magnitude higher according to the shear stresses the flanks of the modelled rate curve does not show a steep decrease like the data. This deviations could be caused by the lack of the model to involve the effect of highly fractured heterogeneous crust on large scale deformations. A specific model modification points towards this view.

Figure 4*B* presents the influence of both, crustal faults and a sequence of horizontal compression on the modelled rate distribution. The change of the uplift rate in percent relates to the maximum of the curve in Figure 4*A*. The fault zones of Figure 2 have been represented by a reduction of the assumed Young's modulus *E*: $[0.5\text{-}1.0] \times 10^6$ N/m^2 to 10% of its value and an increase of the strain rate by two orders of magnitude.

Curve 3 in Figure 4*B* shows the effect of the two "faults" for otherwise identical conditions. The net effect of rate change at the centre section with respect to the flanks is about 8% at the "Rhine-Rhone line" and about 3% at the "Insubric line".

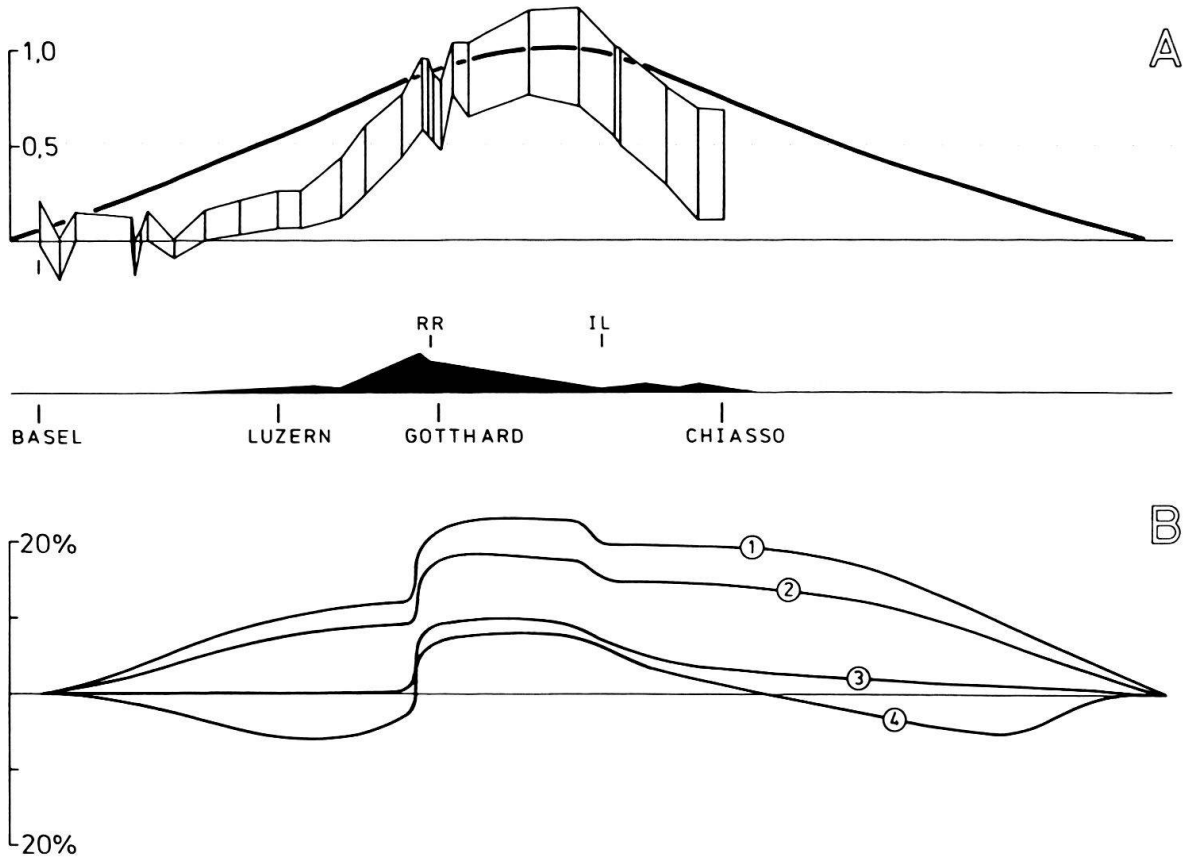

Fig. 4. *A:* Modelled uplift (solid line) compared with recent crustal uplift represented with double standard deviations of yearly elevation changes (as reported in mm/y by GUBLER 1976).

B: Change of modelled rates with respect to the maximum in *A*. "Fault offset" at *RR* (Rhine-Rhone-line), *IL* (Insubric line). Horizontal compression from the right 1 : ① MPa, ② : 10 MPa, ③ : fixed and corresponding to 25 MPa, ④ : 60 MPa.

This result clearly depends on the shape and the mechanical approximation chosen for the faults as well as on the force system. It demonstrates however the behaviour of an activated fault in the model. As far as known no major offset in the rates of uplift has been observed at the fault lines till now. In terms of the model the effect of fault activity remains local.

Beside possible fault activity the figure exhibits how the modelled rate distribution is affected by horizontal compressions attained for 1 MPa, curve 1; 10 MPa, curve 2 and 60 MPa, curve 4. It can generally be concluded that the influence of horizontal compression on the modelled rate with 10% is one order of magnitude lower than the vertical effect for crustal compression up to 60 MPa (600 bar). When compression approaches the 100 MPa (1000 bar) level a squeezing behaviour of the model can be observed which is accompanied by an absolute increase of the uplift rates at the centre.

Although the structure is forced horizontally and vertically the model does not develop towards an upbulging, not even in the upward forced section which is weaker than the surroundings. The limit of this behaviour determined by means of the model is about 70 MPa. The inability of the crustal structure to bulge below the derived limit is a principal point. The amount of about 70 MPa itself is dependent on the structural and density conditions in question. Both aspects will be explained in the context with the modelled stresses.

It can be concluded from the modelled uplift rate curves and the discussed boundary conditions for horizontal crustal compression < 70 MPa that the observed rates of uplift can be explained by the predominance of vertical forces. In particular, the vertical force system responsible for the uplift is associated with the negative isostatic anomaly along the modelled traverse.

5. Modelled stresses

Details of the character of the present-time alpine stress field together with the modelled stresses will provide criteria on the relativity of causal forces for the uplift. In Figure 5 the results of in situ stress determinations (black triangles) are shown along with the amount of modelled horizontal stress components at the upper crustal layer. The Airy-type model for isostatic equilibrium conditions (solid line) reflects the relief of the mountains along the profile. The maximum amount reaches the 30 MPa (300 bar) level. The trend indicated by the data points however is much better approached by the corresponding Airy-Heiskanen isostatic nonequilibrium model with an additional horizontal compression of 10 MPa (100 bar) (dashed line). This reasonable fit will only occur for low (1-10 MPa) horizontal compression. For higher horizontal loading the flanks of stress curves will be lifted up to an overall constant level (NEUGEBAUER & BRÖTZ 1980).

In response to the excess buoyancy associated with the isostatic anomaly the σ_{hor}-curve is obviously shiftet southward (to the right) by 50 km. This leads not only to a much better data fit but in addition to a remarkable coincidence in shape and position of the horizontal stress component and the uplift rate distribution (shaded area) along the traverse. Hence two conclusions can be drawn: Coincidence between in situ stress data, rate of uplift and modelled horizontal stress distribution is

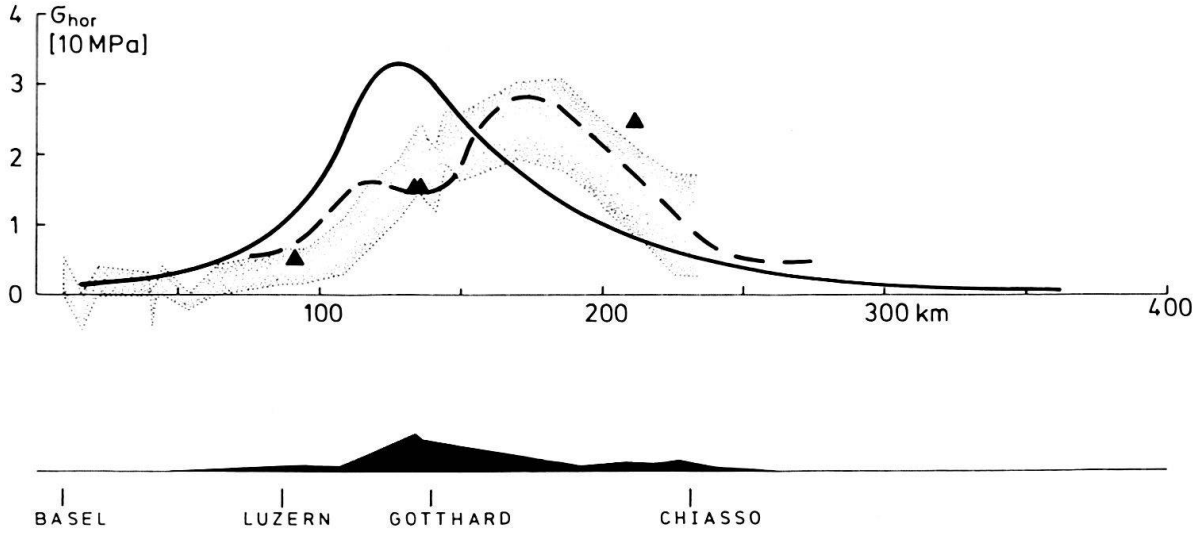

Fig. 5. Excess of horizontal compression, measurement (black triangles, after GREINER & ILLIES 1977). Modelled horizontal stress component: Airy-type isostatic equilibrium (solid line), Airy-Heiskanen isostatic nonequilibrium, and 10 MPa horizontal compression (dashed line). Shape and position of uplift rates after GUBLER (1976) (shaded area).

conducted by the negative isostatic anomaly. Furtheron, the required horizontal compression is necessarily equal or less than 10 MPa.

This tendency can be confirmed by means of the principal stresses. Here we distinguish three different model types. For isostatic equilibrium conditions the orientation of maximum principal stress is directed vertically at the central part of the section and turns towards the horizontal direction like a fan to both sides of the model structure (NEUGEBAUER & BRÖTZ 1980). For the Airy-Heiskanen model at low horizontal compression (1-25 MPa) the pattern is of the type shown in Figure 6*C* (fixed boundary model, 25 MPa). In the case of horizontal compression greater 25 MPa the orientation of the maximum principal stresses becomes adjusted to the horizontal direction from the sides to the centre while the vertically oriented central zone shrinks.

As a function of topographic loading and equivalent buoyancy the vertical maximum principal stresses reach 65 MPa (650 bar) in the range of high mountain relief while the level for the nearly horizontally oriented stresses in the forelands depend on the boundary conditions. As mentioned before they reach 25 MPa for fixed boundaries (Fig. 6*C*).

A compilation of the orientation of maximum compression derived from focal mechanism studies (PAVONI 1976) indicates that the compressive stress field along the traverse is inhomogeneous. The stacked data at a constant depth (Fig. 6*C*) are far from revealing a consistent stress orientation pattern and they contradict to a perfectly horizontal stress orientation.

Maximum shear stresses corresponding to Figure 6*C* concentrate at the central section of the traverse with a maximum of 30 MPa in the middle of the crust beneath the Gotthard region (Fig. 6*B*). Such a distinct maximum with respect to the adjacent area will be built up clearly for the low horizontal compression models. In

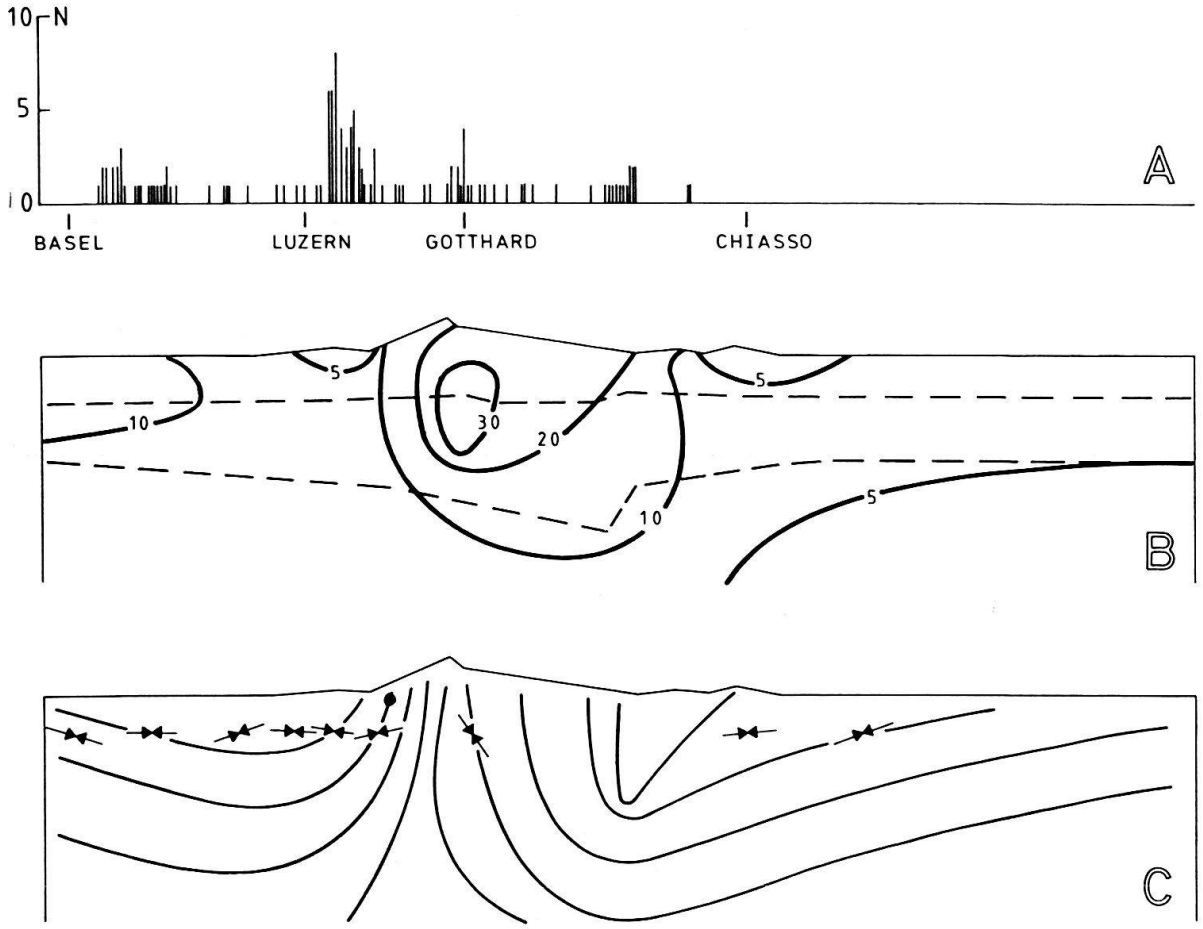

Fig. 6. Orientation of maximum principal stress (*C*) and distribution of maximum shear stresses in MPa (*B*) for the isostatic nonequilibrium model with fixed crustal boundaries. Fault plane data (*C*) at constant depth after PAVONI (1976) and seismicity (*A*) after PAVONI (1977). *N:* number of events. The maximum south of Luzern corresponds to the hinge zone of PAVONI (1977).

terms of crustal uplift and seismicity such a pattern would fit into the idea of a hinge zone discussed before. Although the seismicity (Fig. 6*A*) stacked on the traverse shows a somewhat deviating position for its high frequency (*N*).

6. Discussion and conclusions

For the modelled cross section and the associated Airy-Heiskanen model of crustal densities the horizontal compression necessary to upbulge the alpine mountains can be constrained to values greater 70 MPa (700 bar). The principal mechanism is outlined in Figure 7.

At a fixed boundary (Fig. 7*A*), the maximum principal stresses are oriented mainly vertical within the mountain range while they turn to horizontal in the forelands. To force the mountains to bulge by imprinted horizontal compression one has to exceed the vertical structural stress at the mountains by horizontal stresses (Fig. 7*B*). Therefore, bulging of the crust will only be possible when the effect of topographic loads and buoyancy of the root has been surpassed by horizontal

compression. Before this stage is reached however, any place in the forelands could be bulged earlier and easier than the mountain area itself.

This simple result would contradict to the idea of bulging of mountains in form of a far field mechanism like for the system "Alps-African Plate Push" in general. In terms of our specific model it would constrain the possible horizontal compression to levels lower than 65 MPa (650 bar).

More detailed focal mechanism data could possibly allow to lower the upper limit for horizontal compression to 25 MPa or less (Fig. 6*C*).

The discussed coincidence of in situ stress data with the modelled horizontal stress component and with the shape and position of the measured rate of uplift provides convincing constraints on the horizontal compression to be equal or lower 10 MPa (100 bar). In addition, this result gives strong support to the concept that the

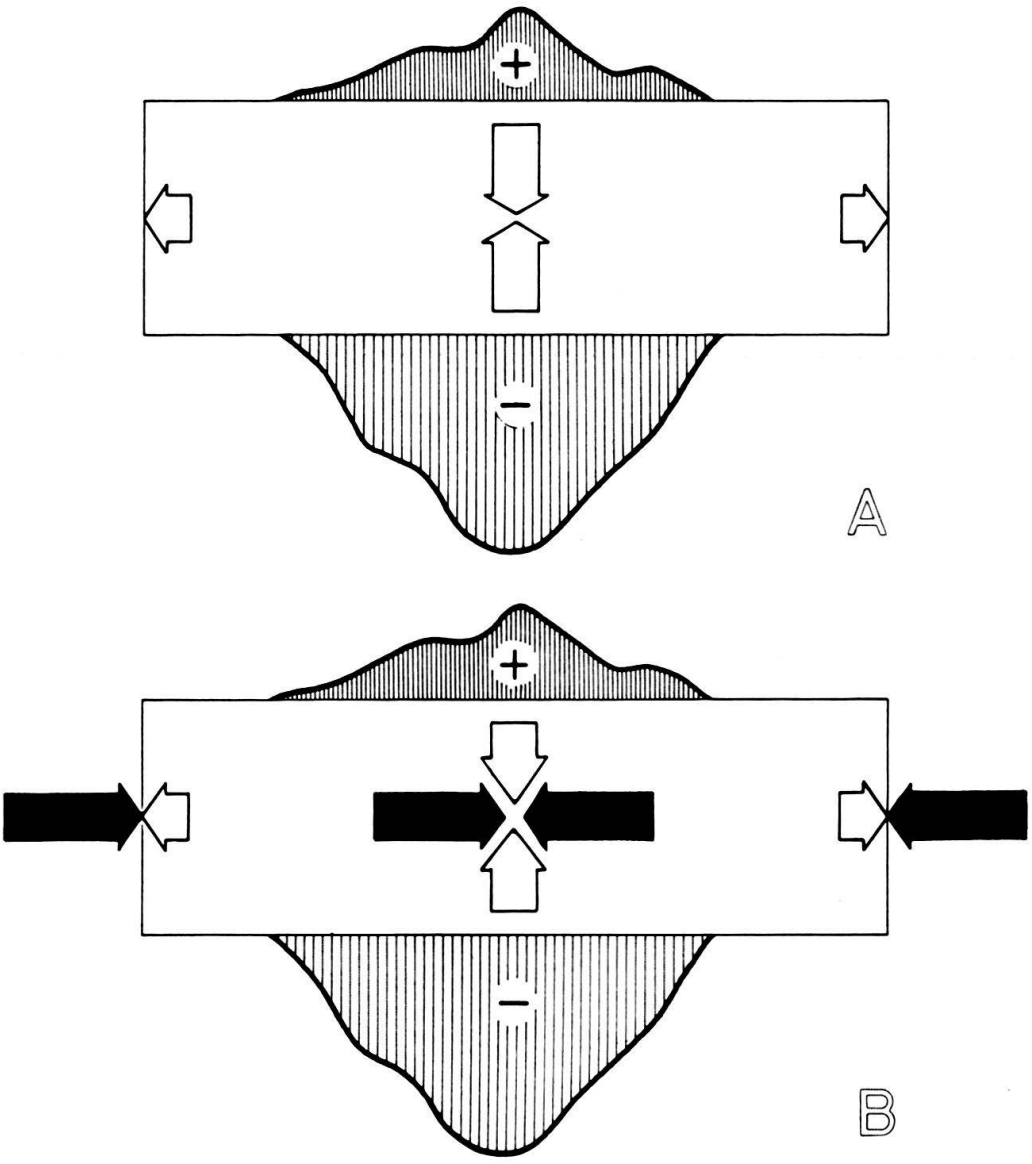

Fig. 7. Principle which demonstrates the inability to bulge a mountain-root system by transmitted horizontal compression. Maximum principal stress conditions for the unloaded crust (*A*) and the loaded crust (*B*).

uplift is related to the negative isostatic anomaly. And finally we should bring up the results of in situ measurements in the northwestern foreland of the Alps which reveal consistently oriented compression of 2 MPa (20 bar) (FROIDEVAUX 1979).

As a general conclusion we state that the data in connection with their improved understanding by means of our numerical models give good evidence that the present activity of the Swiss Alps (crustal uplift and seismicity) is mainly due to the effect of the mountains itself and to minor deviations from isostatic equilibrium.

Acknowledgments

We like to thank our colleagues at Zürich for the support with data. We are grateful to W. Mahler for drafting the figures.

REFERENCES

ASHBY, M.F., & VERRALL, R.A. (1977): *Micromechanisms of flow and fracture, and their relevance to the rheology of the upper mantle.* - Phil. Trans. r. Soc. London *288*, 59-95.

FROIDEVAUX, C., PAQUIN, C., & SOURIAU, M. (1979): *Tectonic stresses in France.* - Trans. amer. geophys. Union *60*, 607.

GREINER, G., & ILLIES J.H. (1977): *Central Europe: Active or residual tectonic stresses.* - Pure and appl. Geophys. *115*, 11-26.

GUBLER, E. (1976): *Beitrag des Landesnivellements zur Bestimmung vertikaler Krustenbewegungen in der Gotthard-Region.* - Schweiz. mineral. petrogr. Mitt. *56*, 675-678.

KAHLE, H.-G., & KLINGELÉ, E. (1979): *Recent activities in gravimetry and physical geodesy.* - Schweiz. mineral. petrogr. Mitt. *59/2*, 207-217.

KAHLE, H.-G., KLINGELÉ, E., MÜLLER, ST., & EGLOFF, R. (1976): *The variation of crustal thickness across the Swiss Alps based on gravity and explosion seismic data.* - Pure and appl. Geophys. *114*, 479-494.

MÜLLER, ST., EGLOFF, R., & ANSORGE, J. (1976): *Struktur des tieferen Untergrundes entlang der Schweizer Geotraverse.* - Schweiz. mineral. petrogr. Mitt. *56*, 685-692.

MÜLLER, ST., KAHLE, H.-G., & KISSLING, E. (1977): *Seismik und Schwere entlang der Schweizer Geotraverse.* - Paper presented at the meeting "Geodynamics and Geotraverses around the Alps", Salzburg.

NEUGEBAUER, H.J., BRÖTZ, R., & RYBACH, L. (1976): *On the dynamics of the Swiss Alps along the Geotraverse Basel-Chiasso.* - Schweiz. mineral. petrogr. Mitt. *56*, 703-706.

NEUGEBAUER, H.J., & BRÖTZ, R. (1980): *The present stress field of the Swiss Alps and its possible origin - Numerical Experiments.* - Submitted to Pure and appl. Geophys.

PAVONI, N. (1976): *Herdmechanismen von Erdbeben und regionaltektonisches Spannungsfeld im Bereich der Geotraverse Basel-Chiasso.* - Schweiz. mineral. petrogr. Mitt. *56*, 696-702.

— (1977): *Erdbeben im Gebiet der Schweiz.* - Eclogae geol. Helv. *70*, 351-370.

RYBACH, L. (1979): *The Swiss Geotraverse from Basel to Chiasso.* - Schweiz. mineral. petrogr. Mitt. *59*, 199-206.

STOCKER, R.L., & ASHBY, M.F. (1973): *On the rheology of the upper mantle.* - Rev. Geophys. (Space Phys.) *11*, 391-426.

ZIENKIEWICZ, O.C. (1977): *The finite element method.* - McGraw Hill, London.