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ABSOLUTE GRAVITY MEASUREMENTS IN SWITZERLAND :

Definition of a base network for geodynamic investigations and for the Swiss fundamental gravity net [1] [2]

Summary

Results of two absolute gravity surveys performed in Switzerland between 1978 and 1979 are presented and discussed in the framework of the uplift history of the Swiss Alps. Five absolute stations have been established as a contribution to the Swiss fundamental gravity net as well as to geodynamic investigations on the Alpine uplift. Two sites (Interlaken–Jungfraujoch) form the end points of a calibration line for field gravimeters. The gravity range of this line amounts to $605 \times 10^{-5}\ ms^{-2}$ *(= 605 mgal). It can be traversed in a relatively short time interval of less than 3 hours. Two other sites (Brig and Chur) are located in the area of the most negative gravity anomalies and highest uplift rates encountered in Switzerland. They serve as reference stations for a more extended gravity net for studying non–periodic secular gravity variations associated with the Alpine uplift.*

1. Introduction

Intensive geodetic and geophysical work has been carried out in the Swiss Alps over the past 10 years in order to study the present day pattern of recent crustal movements, and attempts have been made to explain them in terms of crustal and upper mantle structure within the framework of plate tectonics. These studies were an integral part of the program sponsored by the Swiss National Committee for the International Geodynamics Project (IGP). A review of the activities related to this program was presented in the final IGP–report of Switzerland (Mueller and Oberholzer, 1979). A central theme of the IGP was focused on the question of the driving mechanism for global plate tectonics. The problems are not yet completely solved, and efforts are still being made to elucidate the nature of forces driving the major lithospheric plates. In the case of

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the Alps one is confronted with uplifting forces which are still being active as can be inferred from geochronological studies, precise levelling, an analysis of the seismicity pattern and gravity measurements. Gravity methods relevant to this question include computation and interpretation of various kinds of gravity anomalies, such as Bouguer or isostatic anomalies, as well as monitoring and interpreting non–periodic secular changes of the gravity field. This concept has been pursued in the recent past in order to shed light on the uplift phenomenon. The purpose of this paper is to present and discuss results of absolute gravity measurements which have been performed in this context in 1978 and 1979.

2. Recent Crustal Movements

The present day kinematic pattern can be described by results of repeated precise levelling carried out in Switzerland since 1865 (Hirsch and Plantamour, 1891 ; Swiss Geodetic Commission, 1901). From repetitions of the Swiss precise levelling net uplift rates have been deduced (Jeanrichard, 1972, 1973, 1975 ; Gubler, 1976 ; Kobold, 1977 ; Gubler et *al.,* 1981). If a reference bench mark is considered in the Swiss Molasse basin (Aarburg – near the southern border of the Swiss Jura mountains) the annual uplift rates form the following pattern : They increase almost linearly from Aarburg to the south when approaching the central Alpine chain reaching values of about 1 mm/y in the Aar/Gotthard massifs. These two crystalline massifs are separated by the Urseren zone which forms part of the Rhine/Rhone valley, a prominent tectonic feature which is associated with moderate seismicity and very pronounced negative gravity anomalies.

South of the crystalline and metamorphic rocks exposed in the Gotthard massif the uplift still increases and reaches about 1.4 mm/y in the Lepontine area. To the east and west of the Urseren zone the annual elevation changes increase and attain values of 1.7 mm/y near Chur (in the canton Graubünden) as well as near Brig/Visp (in the canton Valais). While the order of magnitude of these uplift rates is concordant with denudation rates (Jaeckli, 1958 ; Clark and Jaeger, 1969), there are significant lateral and temporal changes (Aegerter, 1979) as can be inferred from cooling age determinations on rock–forming minerals (Wagner et *al.,* 1977) and geological studies (Hsü, 1971, 1979 ; Gruenenfelder and Koeppel, 1980 ; Truempy, 1973, 1980).

An uplift rate of 0.4 mm/y was deduced from apatite fission track ages for the Monte Rosa area (Wagner and Reimer, 1972). According to Wagner et *al.* (1977) the uplift rate increased in the Monte Rosa area since 6 m.y. to reach a value of 0.7 mm/y in the recent past. Another area of increase in uplift rate is the Simplon–Antigorio zone where the rate increased from 0.7 mm/y to 1.1 mm/y at about 3 m.y.b.p. In contrast to these accelerated uplift zones the Ticino area has shown a decrease in upheaval from 1.3 mm/y at about 20 m.y.b.p. down to 0.4 mm/y since about 7 m.y. The Gotthard massif, on the other hand, displays a uniform uplift of 0.6 mm/y since 19 m.y. (Wagner et *al.,* 1977).

The question arises how the deep crustal structure relates to the present day (Gubler, 1976 ; Gubler et *al.,* 1980) and past (Wagner et *al.,* 1977) kinematic pattern. In order to approach this problem attempts have been made to determine P wave velocities (Mueller et *al.,* 1976) as well as density values (Kahle et *al.,* 1980) as a function of depth. The elucidation of crustal structure in terms of V_p velocities has become possible after numerous long–range seismic profiles have been recorded and evaluated (Mueller and Talwani, 1971 ; Mueller et *al.,* 1976 ; Alpine Explosion Seismology Group, 1976 ; Ansorge and Mueller, 1979 ; Mueller et *al.,* 1980). One of the major findings was the existence of two low–velocity zones (Mueller et *al.,* 1976 ; Egloff and Ansorge, 1976 ; Egloff, 1979) which can be envisioned as decoupling horizons for the overlying crustal slabs (Mueller, 1977 ; Hsü, 1979). This hypothesis provides a reasonable explanation for the numerous nappe structures encountered in the Alps and at the same time it leads to a better understanding of the observation that there are significant lateral changes in relative uplift and subsidence. For the determination of the density distribution (and its eventual temporal variation) it is necessary to measure and interpret the gravity field both in a relative and absolute sense.

3. Gravity Anomalies

Over the past 8 years efforts have been made to complete the new Bouguer gravity anomaly map of Switzerland (Klingelé and Olivier, 1981). The most prominent feature of this map is the pronounced decrease in gravity when approaching the central Alpine chain. The major constituent of this decrease is due to the effect of increasing crustal thickness (Kahle et *al.,* 1976 a, b). The lowest values (− 180 mgal) are found along an ENE–WSW oriented zone which coincides with the Rhine / Rhone line. From a comparison with the uplift rates determined by precise levelling it is tempting to assume that the uplift may be influenced by buoyancy forces originating from mass deficits lying underneath this zone (Kahle et *al.,* 1980). In order to evaluate this observation quantitatively isostatic corrections were applied to the Bouguer anomalies. The corresponding isostatic anomaly map (Klingelé, 1980) reveals a striking correlation between the lateral change of uplift rates and horizontal isostatic gradient. The observed interrelationship between these two sets of data calls for the desirability to measure temporal changes in gravity – most likely being associated with the contemporaneous uplift. By simultaneously performing precise levelling measurements and monitoring the gravity field some further constraints can be placed on the nature and temporal mass transfer at greater depths. This information can then lead to a better understanding of the driving mechanism of the present day movements of the Alps if it is combined with in–situ stress measurements (Illies and Greiner, 1976, 1978 ; Greiner and Illies, 1977), focal plane solutions of earthquakes (Pavoni and Mayer–Rosa, 1978 ; Mayer–Rosa and Mueller, 1979) as well as with explosion seismic data and heat flow measurements (Rybach, 1979 ; Rybach and Finckh, 1979).

4. Absolute Gravity Measurements

A project of measuring absolute gravity in Switzerland has been initiated in 1978 in a joint effort by the ETH Zürich, the University of Trieste and the Istituto di Metrologia, Torino. Five absolute gravity stations of high accuracy were established including a calibration line for field gravimeters between Interlaken and the Jungfraujoch in the Berner Oberland.

4.1. Instrumentation

In principle, each physical experiment which involves the gravity acceleration can be used to measure the absolute value "g". However, the most promising results have been achieved by using the free fall (Faller, 1965 ; Faller et *al.,* 1978 ; Hammond and Iliff, 1978) and the symmetrical free rise and fall (Sakuma, 1971) of a body . With the transportable absolute gravity meter developed by the Istituto di Metrologia G. Colonnetti (IGMC) the gravity measurement is based on the observation of the symmetrical free rise and fall of a body in the earth's gravitational field. The main advantage of this method, compared to the simple fall, is a relative freedom from residual air resistance and a higher accuracy in time measurements, owing to the symmetry of the motion.

In the measuring experiment a body is projected vertically upwards and, in its rise and fall, it crosses twice two stations separated by a distance H. Two time intervals, T and t, corresponding to the two passages across the lower and upper stations, respectively, are measured. The value of the acceleration g due to the gravity force of the earth is given by :

$$g = \frac{8H}{T^2 - t^2} \tag{1}$$

The vertical gradient of g is assumed to be constant along the entire trajectory (about $30\ \mathrm{cm}$). The value of g obtained from the above formula corresponds to a point situated at height

$$z = \frac{H}{6} + \frac{h}{3} \approx \frac{H}{6} \tag{2}$$

from the apex of the trajectory downwards. h is the distance between the apex and the upper station and is negligible with respect to H. The vertical gradient of gravity is measured by means of a LaCoste & Romberg Model D gravimeter. Normally the gravity difference between the reference level and the height z is measured. The computed vertical gradients are listed in the tables of the results. The distance H is measured by means of a Michelson interferometer *(Fig. 1)*. The projectile is a corner cube (C1) which forms the movable mirror of the interferometer. A second corner cube (C2) is placed on the inertial mass of a long–period seismometer (natural period $\sim 20\ \mathrm{s}$) and forms the reference mirror. The radiation of a stabilized He–Ne laser provides the standard unit of length whereas an atomic frequency clock provides the standard unit of time.

The measurement begins at a pre–determined but arbitrary instant on the upward trajectory (no material standard unit of length is used). At that point fringe counting begins by means of a bi–directional counter activated by the signals of two photomultipliers P_a and P_b. Simultaneously, measurement of the total flight time begins as well. Another time counter is reset by each fringe in the rise and is stopped only by the first fringe in the fall motion, owing to phase relation inversion of the signals from the photo–detector at the apex of the trajectory. This time interval is the quantity "t" in equation (1).

The upper station is placed at the last fringe in the upward motion. If N is the total number of fringes recorded in the upward motion and λ the wavelength of the laser beam then

$$H = N\lambda/2 \tag{3}$$

In the downward motion the counter counts the number of fringes in decreasing order. It stops counting of time T when it reaches fringe 0.

4.2. Error analysis

The value of the laser light wavelength and its stability influence the distance measurement. A maximum relative error of 5×10^{-9}, corresponding to $\pm 5\ \mu\mathrm{gal}$ is

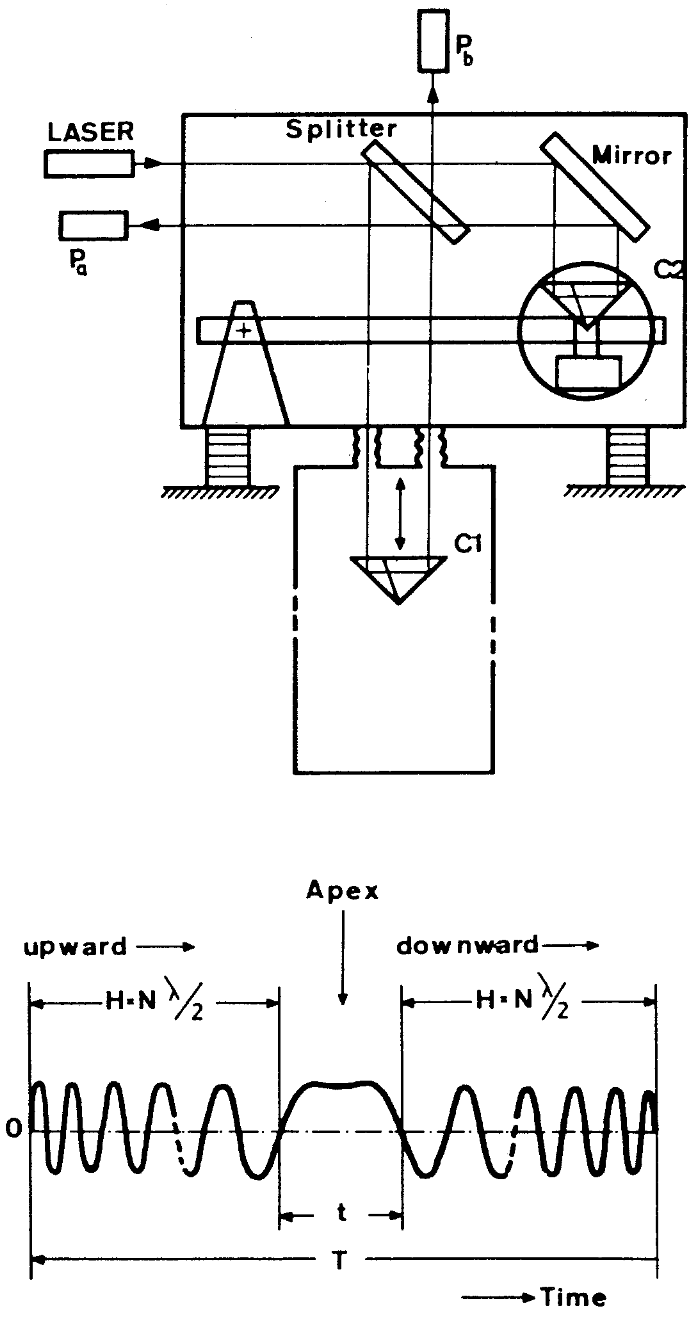


Fig. 1 — Principle of the absolute gravity measurement by means of a Michelson interferometer.

C1 = Flying projectile (corner cube)

C2 = Resting corner cube

P_a, P_b = photomultipliers

expected. Microseismic noise influences the determination of distance as it alters the position of the fixed mirror. The positioning of the fixed mirror on the inertial mass of a long–period seismometer reduces these disturbing effects considerably. The mechanical shocks of the catapult on the movable corner cube can be an additional source of disturbance. In order to avoid this effect measurements begin with a pre–determined delay with respect to the mechanical release of the catapult.

Deviations from the verticality of the laser beam as well as of the trajectory of the corner cube must be less than 10^{-4} *rad* if errors in g should be less than $5\ \mu$gal. Moreover, rotation rates of the corner cube must be less than $0.3\ rad/s$.

The stability of the rubidium time standard is of the order of 10^{-10}. An electronic counter with ± 1 ns resolution is used to determine time T. The "start" and "stop" pulses obtained from the fringe counter are affected by the delay time of the circuits used. This systematic error may be determined with an accuracy of ± 0.5 ns. The error in the determination of t is higher due to the fact that a counter with ± 100 ns resolution is used. However, since $t << T$ this error is negligible.

A typical example of error evaluation is given in the following table :

	Source of error	uncertainty (μgal)
(1)	Laser wavelength	± 5
(2)	Beam direction	± 5
(3)	Time interval	± 6
(4)	Gradient of g	± 2
	Net uncertainty	± 10

4.3. Previous measurements

Since 1976 the IMGC absolute gravity meter has been used in intensive field programs. 17 absolute stations have been established in Europe and 6 in North America (Cannizzo et *al.,* 1978 ; Marson and Alasia, 1979). During the course of these field projects some stations have been re–visited several times in order to control the instrumental long–term behavior. The repeatibility of the measurements is shown in *Table 1.* Repeated measurements at Sèvres have enabled us to compare the results of the IMGC absolute gravity apparatus with the one of Sakuma (also included in *Table 1*). The comparison of results obtained by absolute gravimeters employing different measuring methods was a point of high concern. The IMGC symmetrical free–rise and–fall and the Hammond – Faller free–fall instruments have been compared at Bedford and Denver, U.S.A. The results show an agreement within $20\ \mu$gal (Marson and Alasia, 1979). A more recent comparison of the current AFGL instrument at Bedford (Hammond and Iliff, 1978) shows also an agreement within $20\ \mu$gal.

The absolute gravity measurements at European stations have been performed in order to control the scale and the linearity of the International Gravity Standardization Net of 1971 (IGSN 71) (Morelli, 1971). Actually, 14 stations have been proposed by the International Gravity Commission (IGC) in a special resolution to serve as an absolute calibration line running from Hammerfest (Norway) to Catania (Italy) (8^{th} I G C Meeting,

Table 1

Repeatability of the measurements in the same station

Station and Date	g_r (μgal)
Sèvres, May 1976	980 925 892 ± 10
Sèvres, June 1976	980 925 902 ± 9
Sèvres, January 1977	980 925 896 ± 10
Sèvres, March 1977	980 925 906 ± 10
(Sèvres A_3 by SAKUMA)	980 925 900 ± 2
Gävle, July, 1976	981 923 527 ± 9
Gävle, August 1976	981 923 533 ± 9
Gävle, September 1976	981 923 524 ± 11
Torino, July 1976	980 534 256 ± 11
Torino, October 1976	980 534 251 ± 11
Torino, June 1977	980 534 259 ± 10
Bedford, October 1977	980 378 671 ± 10
Bedford, December 1977	980 378 675 ± 11

g_r = gravity value reduced to reference level (floor or pillar surface) ± net uncertainty.

1978). Finally, absolute values have been included in the adjustment of the new first–order gravity nets of Italy (Marson and Morelli, 1978) and Germany (Boedecker et *al.,* 1979).

While the previous measurements were mainly concerned with calibration problems and the establishment of fundamental gravity nets, the Swiss project is, in addition, aimed at contributing to the solution of the above–mentioned geodynamic problems.

5. Selection of Sites and Data Presentation

Fig. 2 displays the locations of the Swiss absolute gravity stations on a generalized tectonic map. While station "Zürich" is intended to serve as a fundamental site, the stations "Interlaken" and "Jungfraujoch" were selected in order to establish a calibration line of an extended range for relative field gravimeters (Klingelé and Kahle, 1981). The entire gravity range covered by this line amounts to ~ 605 mgal which can be observed within a time period of less than 3 hours. The remaining two stations at "Brig" and "Chur" are located along the Rhine / Rhone line where the highest uplift rates have been observed.

Results of the absolute gravity determinations are listed in *Table 2.* About 100 independent measurements have been taken at each station. Earth tidal corrections using an amplification δ factor of 1.14 have been applied to each single value by means of a computer program. *Figure 3* shows the histograms of the recorded data. Even if the average microseismic noise was of small amplitude ($< 1\ \mu m$) the presence of low frequency components at the sites Interlaken, Jungfraujoch and Brig may have affected the scatter of the measurements. Detailed station descriptions of the absolute sites will be presented in a later (final) report.

6. Discussion and Conclusion

Recent studies of seismicity in Switzerland are based on a new seismic station network monitored by the Swiss Seismic Service (Mayer–Rosa and Mueller, 1979). According to these records moderate seismic activity during the past 10 years was mainly centered in the cantons Graubünden and Valais. A comparison of the epicenter map with the gravity map seems to indicate a correlation between these two sets of data. It is, therefore, tempting to assume that the seismic activity and the prominent gravity lows in the cantons Graubünden and Valais may be, at least indirectly, due to the same cause. A similar correlation has been observed earlier in the rift systems of Central Europe and East Africa (Mueller, 1970). In addition, the pronounced gravity lows seem to coincide with a significant increase in uplift rates determined from precise levelling. In this context it must be noted that the gravity minima are not yet fully understood. Efforts are being made to interpret them by including also geothermal considerations (Werner et *al.,* 1976 ; Kahle and Werner, 1980). Furthermore P–wave velocity distribution and seismically determined depths of the crust mantle boundary (Egloff, 1979 ; Mueller et *al.,* 1980), as well as lateral changes in the thickness of the lithosphere (Panza and Mueller, 1978) will be incorporated in the gravity interpretation. Simultaneously the surface density distribution for the major tectonic units is being determined in order to apply geological corrections to the Bouguer anomalies. While these methods provide information about the deep structure of the earth's crust and upper mantle under the Alps the basis of studying non–periodic secular changes in gravity – as presented in this paper – will facilitate an understanding of the kinematic phenomena presently observed in the Alpine chain.

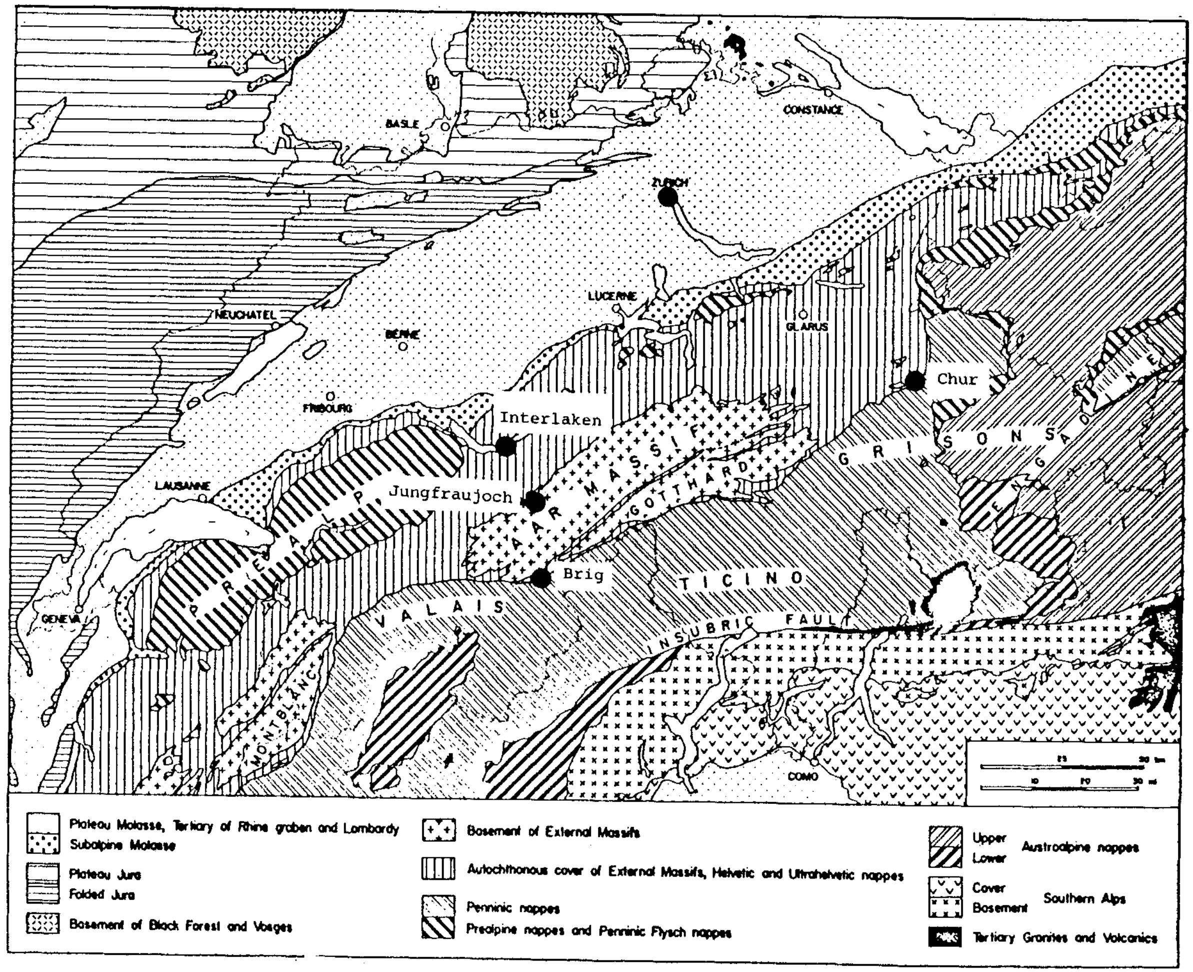


Fig. 2 – Locations of the Swiss absolute stations measured in the period 1978 / 1979. Generalized geology after RAMSAY and MILNES, Geological Institute, ETH Zürich.

Table 2

Absolute gravity measurements in Switzerland

Site	Date	N_m	g_f	m	M	h	$\frac{\partial g}{\partial h}$	honk	g_r
Zürich	June 7-8, 1978	100	980 647 651	25	2.5	758	258	22	980 647 895 ± 10
Chur	June 14-16, 1978	100	980 453 657	23	2.3	738	206	21	980 453 856 ± 11
Interlaken	Aug. 23-24, 1979	132	980 505 292	39	3.4	725	236	21	980 505 484 ± 10
Jungfraujoch	Aug/Sep. 30-1, 1979	114	979 900 434	38	3.6	712	382	21	979 900 727 ± 10
Brig	Sep. 22-24, 1979	114	980 407 350	39	3.7	659	217	20	980 407 513 ± 10

N_m = Total number of measurements at each station

g_f = final mean value of gravity [μgal] at height h [mm] above pillar surface corrected for electronic delay

g_r = gravity value reduced to reference level (floor or pillar) ± net uncertainty [μgal]

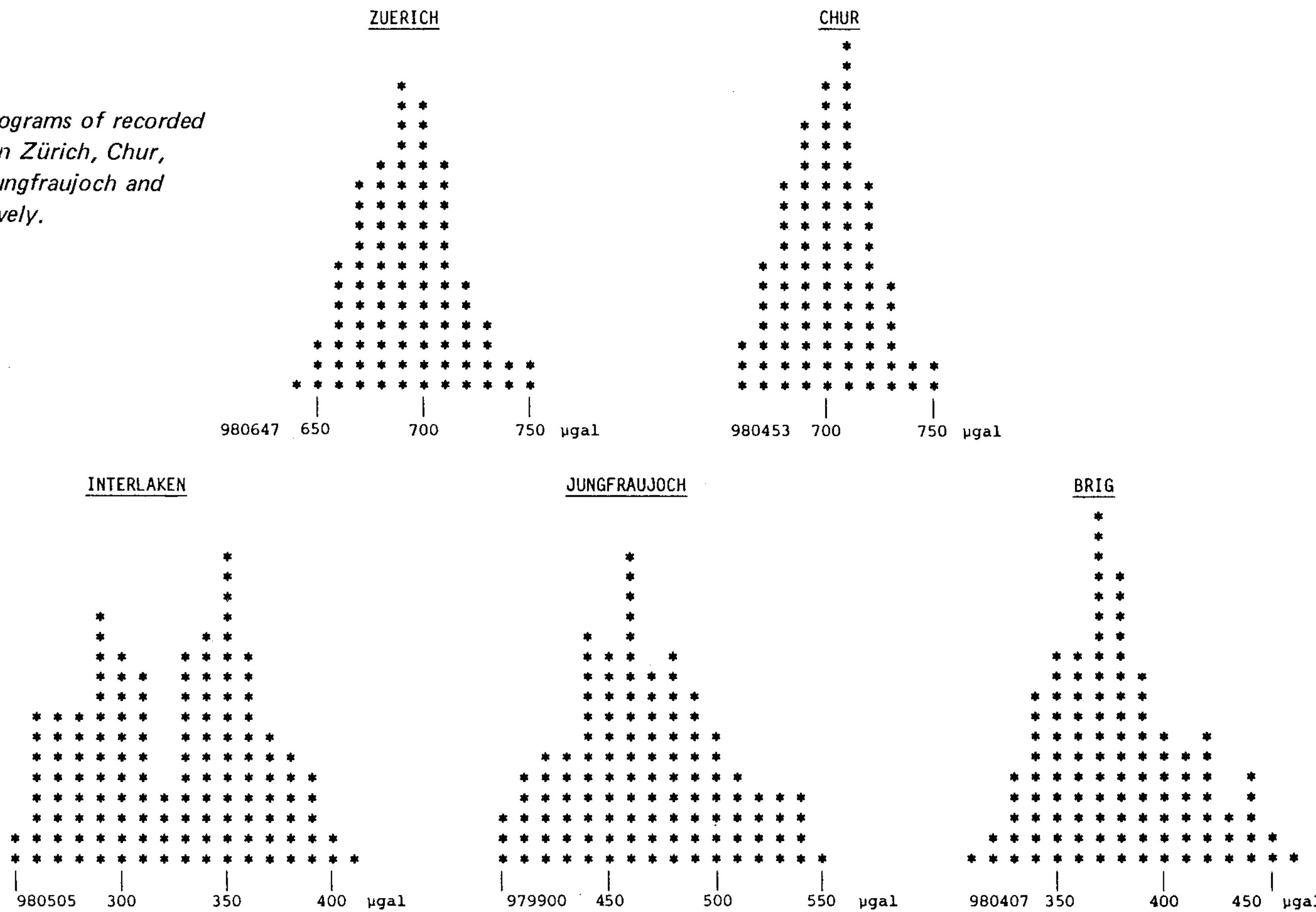
m = standard deviation

M = standard error

$\frac{\partial g}{\partial h}$ = vertical gravity gradient [μgal/m]

honk = Honkasalo's tidal correction term [μgal]

Fig. 3 — Histograms of recorded gravity data in Zürich, Chur, Interlaken, Jungfraujoch and Brig, respectively.



Besides fault – plane solutions of earthquakes (Mayer–Rosa and Pavoni, 1977 ; Pavoni and Mayer–Rosa, 1978 ; Mayer–Rosa and Mueller, 1979) temporal changes in gravity combined with precise–levelling will help to elucidate the nature of the ongoing crustal movements which are most likely connected with plate tectonic activity in the contact zone between the Eurasian and African (through its Adriatic promontory) plates. For this reason a geodetic project has been initiated simultaneously with the gravity program in order to obtain two independent sets of information about the uplift phenomena (Chaperon et *al.,* 1981).

In this paper we have documented the initiation of absolute gravity measurements which are intended to serve as a basis for future geodynamic studies. Repeated absolute gravity determinations will enable us to evaluate variations of the gravity field over a long period of time because the measurements are independent of internal variations of the instrument (for instance, changes in scale factors). Moreover, the reference datum provided by absolute gravity sites will permit to distinguish between local and regional effects, resolving the internal ambiguity associated with relative networks.

Gravity nets based on absolute stations constitute a powerful mean for geodynamic investigations since the average accuracy of absolute determinations ($\pm 10\,\mu$gal) has become comparable to relative measurements. Finally, it should be mentioned that efforts are being made to improve the accuracy of the IMGC transportable absolute gravity meter within the next few years.

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Abbreviations :

PAGEOPH = Pure and Applied Geophysics
SMPM = Schweizerische mineralogische und petrographische Mitteilungen
VPK = Vermessung, Photogrammetrie, Kulturtechnik.

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