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Some Problems of Large-Scale Gravity Interpretation

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Abstract. Linear regression and interrelations of mean free air and isostatic gravity anomalies with other geophysical parameters such as upper mantle density variations, depth of M-discontinuity, and heat flow are studied for Germany and Central Europe. In spite of local interdependences large scale correlation is only found for gravity and heat flow values. Gravity data are used in terms of mean anomalies, geoid undulations and single layer density variations (corresponding to a lithosphere of constant thickness).

Key words: Geoid – Gravimetric interpretation – Correlation of gravity with crustal parameters – Gravity field in Germany – Heat flow versus gravity in Europe – Gravity anomaly statistics – Isostatic reduction of gravity.

1. Introduction

Large-scale gravity interpretation has found increasing application since (1) the low harmonics part of gravity became available from satellite orbit analysis, and (2) long range gravity anomalies, as obtained from surface gravimetry, gained more reliability through the application of long-range gravity nets and from filling the existing gaps in the world gravity field. In the present investigation the gravity potential and the corresponding anomalies were considered within limited areas where spherical harmonics of degrees $n \leqq 18$ and mean anomalies of block size $d' \geqq 6$ min of arc are of main concern. The trends are typically given by harmonics of degree $n < 17$.

When absolute values are considered, zero degree terms in the harmonic expansion are of special interest. But in this interpretation mainly variations, *i.e.* relative values, are relevant.

Numerical values for the lower harmonic part are those of the Goddard Earth Model (GEM); additional sources of data information applied in the study are given by Groten and Rummel (1974) and Groten (1974).

It is the aim of the present study to represent the regional gravity field in different ways and to point out problems arising in *regression* studies of gravity with other geophysical parameters and fields.

Correlation being a measure of *linearity* of interpendence has not been used in this study because it is too strongly affected by low harmonics.

Gravity is represented by free air and isostatic anomalies, geoid heights and single layer densities.

In *regional* studies correlation of geoid undulations with other geophysical parameters, like depth of M-discontinuity etc., was previously investigated, *e.g.*, by Durbin (1966), Wolf (1971), Pick and Jabkucova (1972), Groten (1966). Discussion of long-range geoid heights was done, *e.g.*, by Kahle and Talwani (1973).

Statistical regression studies are not hampered by the nonuniqueness resulting from Stokes' theorem which affects the interpretation by *models* deduced from N or Δg. Even though statistical results are less specific than those of model investigations they are good tools in prediction.

In general, methods of *local* gravity interpretation differ from those of *global* interpretation; but the evaluation of appropriate lithospheric models can in both cases be useful in investigating *detailed* distribution of matter; *e.g.* (Watts and Cochran, 1974a, b; Watts and Talwani, 1974a, b). However, statistical inferences as *e.g.* widely applied by Woollard (1972) yield mainly *general* information.

In paragraphs 2 to 4 the gravimetric quantities used in the investigations are defined and described where the reasons for applying isostatic anomalies (according to Airy-Heiskanen) are specificly given. The details of the numerical results shown in paragraph 5 are discussed in paragraph 6.

2. Geoid Computations and Topographic Effects

In large-scale interpretation mean free air anomalies are often used instead of Bouguer anomalies because the correlation of mean free air anomalies of large blocks with topography is smaller than the correlation of mean Bouguer anomalies. In many areas isostatic anomalies are even less related to topographic features. Short period effects of the topography are eliminated or reduced in the potential W, too, particularly in its perturbation part:

$$T = W - U \tag{1}$$

where U is the normal potential. The same is true with geoid heights

$$N = T/\gamma \tag{2}$$

where $\gamma = -\partial U/\partial n$ is normal gravity and n is the surface normal. Using Stoke's integral formula

$$N = \frac{R}{4\pi\gamma} \iint_E \Delta g \, S dE \tag{3}$$

(where E = earth's surface,
dE = element of E,
$\Delta g = g - \gamma$ = gravity anomaly,
R = mean radius of the earth,
S = Stoke's function and
$g = -\partial W/\partial n$ = observed gravity).

N is found from gravity anomalies. In the present investigation N as obtained from formula (3) is combined with satellite data using the superposition method given by Groten and Rummel (1974).

When S is considered as a low pass filter function the application of the integral formula (3) might simply be taken as a method for reducing topographic effects of Δg.

In the present investigation it seemed appropriate to rely on a statistical approach which might be summarized by linear and non-linear regression formulas as

$$A = C + \sum_i a_i c_i \text{ (+non-linear terms)} \tag{4}$$

where A may stand for Δg or N,
a_i are linear regression coefficients,
C is a constant,
$c_1 = h$, topographic height and oceanic depth,
$c_2 = H'$, mantle depth,
$c_3 = v$, mantle velocity,
$c_4 = V$, crustal velocity; the list may be extended by geological and similar parameters.

Since the Bouguer-correction is linear in h and, moreover, the terrain correction as well as the isostatic corrections are to some extent linear in h (Groten and Reinhart, 1968) Eq. (4) in its linear form can be applied in most cases.

The geoid height N as given by Eq. (3) is only a first order approximation. But detailed investigations of the second order approximations as obtained by taking into account Molodensky-type corrections (Brennecke *et al.*, 1975) show that corresponding corrections are always less than 0.4 m and, consequently, do not affect the result given below. This statement holds for the part of the spectrum discussed in the present investigation and should not be generalized because the numerical integration of the correction formula depends strongly on the local statistical behavior of the parameters from which these corrections are evaluated.

3. Single Layer Model

Beside N and Δg gravity has been used in a third way by computing the density of a single layer at the earth surface (Helmert, 1884)

$$\mu' = \frac{1}{2\pi f}\left(\Delta g + \frac{3\gamma N}{2R}\right) \tag{5}$$

in its spherical approximation (where f = Newton's gravitational constant). Further, according to Heiskanen and Moritz (1967),

$$\mu=2\pi f\mu'=\Delta g+\frac{3T}{2R}. \tag{6}$$

When Eqs. (3) and (6) are combined a formula for $\mu(\Delta g)$ is found; on the other hand, $\mu(N)$ is obtained on inserting the inverse integral formula to Eq. (3) in (6) as shown by Chovitz (1974). Consequently, several formulas for evaluating μ and μ' are available.

If Δg and N are supposed to be produced by density variations ρ within a lithospheric layer of constant thickness H we get from

$$\rho=\mu'/H \tag{7}$$

together with Eq. (5)

$$\rho=\frac{1}{2\pi Hf}\left(\Delta g+\frac{3\gamma N}{2R}\right) \tag{8}$$

or, in terms of spherical harmonics, Δg_n,

$$\rho=\sum\rho_n \tag{9}$$

where

$$\rho_n=\frac{\Delta g_n}{2\pi Hf}\left(1+\frac{3}{2(n-1)}\right) \tag{10}$$

and

$$N=\frac{R}{\gamma}\sum\Delta g_n/(n-1). \tag{11}$$

Consequently, for $n>91$ we get

$$\rho_n\doteq\frac{\Delta g_n}{2\pi fH} \tag{12}$$

neglecting an error of 1.5 percent.

4. Isostatically Reduced Gravity Values

The classical isostatic concepts have undergone several revisions during the last time; see, *e.g.*, MacDonald (1963), Jacoby (1973b), Artyushkov (1974). They can seriously affect the local geophysical interpretation; detailed isostatic reductions where regional variations of Moho-depth and density as well as deviations from isostatic equilibrium are taken into account, are seldom feasible in large-scale gravimetric interpretation. Consequently, gravity anomalies reduced according to the Airy-Heiskanen method with compensation depth $D=30$ km have been used in computing geoid heights and the isostatically reduced single layer density. When Moho depth data as given by Giese and Stein (1973) are compared with the above value of D it is seen that the deviations are not too large. Moreover, it should be kept in mind that in those areas where the depth of the Moho is greater than D, as in the Alps, the mountain roots according to the isostatic concept are at depth $\geqq 40$ km. In the whole, the isostatic reduction is considered as a working concept in order to reduce the numerical values of Δg and to have a model which might largely be independent of topographic effects.

When ρ as given by Eq. (7) is evaluated from isostatic gravity for a lithospheric layer of constant thickness $H = 100$ km with laterally varying density it is supposed to be more appropriate for interpretation in all cases where large-scale topographic effects should be eliminated or, at least, reduced.

In Airys classical isostatic concept the depth of compensation D is chosen in such a fashion that there is zero correlation between isostatic $\Delta g(D)$ and station elevation h. This method is basicly equivalent to Nettleton's well known principle as applied to free air anomalies in density determinations. When this principle is applied the regional regression coefficients of isostatic anomalies $\Delta g(h)$ can be plotted for different D-values. In case of isostatic equilibrium the most probable D is then found for zero correlation.

The necessity of revised concepts with respect to the classical theory becomes evident on inspecting Figs. 1 and 2 where for Holopainen's (1974) isostatic anomalies corresponding linear regression coefficients are shown in revised form for different numerical values of depth of compensation D. The *large-scale* application of Nettleton's principle, *i.e.* zero correlation of topography with reduced gravity, which has previously been critizised (Groten and Reinhart, 1968) with free air anomalies leads to distorted values for the Moho-depth $\leqq D$ if it is applied to these isostatic anomalies with varying depth of compensation D. For it is seen from Figs. 1 and 2 that D found for zero regression coefficients is in most cases incompatible with any reasonable Moho depth values. Discrepancies are only partly explained by deviations from isostatic equilibrium.

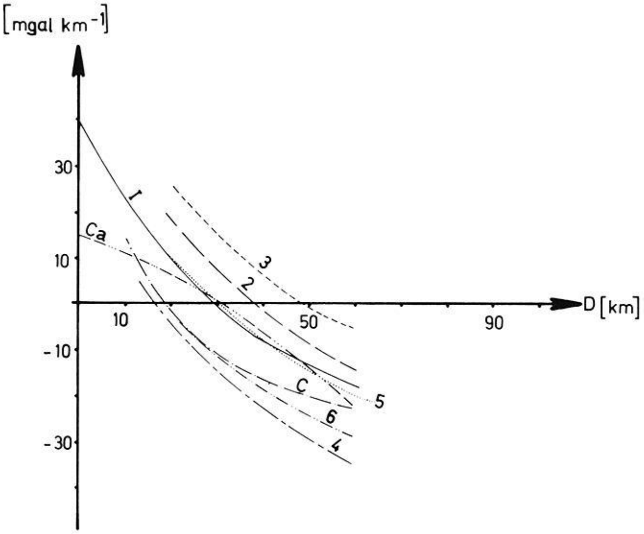

Fig. 1. Regression coefficients (mgal/km) for isostatic anomalies of variable compensation depth (after Airy-Heiskanen) $0 < D < 60$ km; *1*, *2* Northern Italy; *3* Northern Austria, *4*; *Ca* Eastern Alps; *5*, *6* Central part of Austria, *C* Central Alps

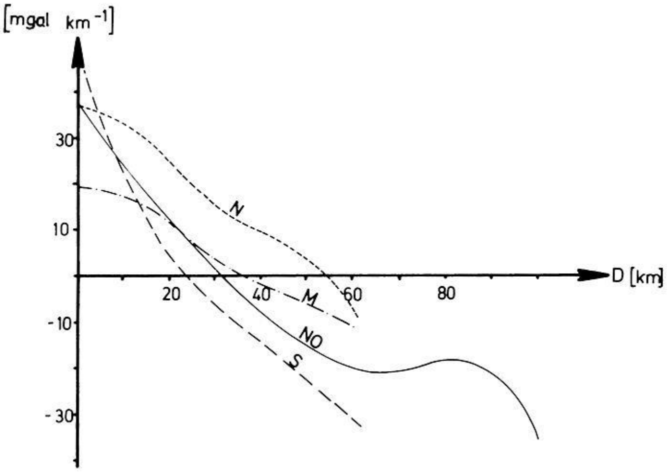

Fig. 2. Regression coefficients (mgal/km) for isostatic anomalies of variable compensation depth (after Airy-Heiskanen) $0<D<100$ km; *N* Northern Sweden; *M* Central part of Sweden; *S* Southern part of Sweden; *No* Norway

When isostatic and other anomalies are considered from a statistical view point variances are found to be

$$\text{var}(\text{isostatic } \Delta g)=207 \text{ mgal}^2$$

$$\text{var}(\text{free air } \Delta g)=400 \text{ mgal}^2$$

$$\text{var}(\text{Bouguer } -\Delta g)=835 \text{ mgal}^2$$

for 6′ by 10′ mean values within F.R. of Germany. The autocorrelation function of free air anomalies is not very different from the autocorrelation of isostatic anomalies as seen from Fig. 3.

Together with the variances the autocorrelation functions are considered as a global measure of model truth, *i.e.* the steeper the descent of the autocorrelation function and the smaller the deviations of the covariance (*i.e.* autocorrelation times variance) from zero the better is the model applied in the reduction of Δg.

In case of Bouguer anomalies the large effects of subterranean mass deficits according to the isostatic theory are mainly reflected by the relatively strong autocorrelation within the first few hundred kilometers and, to some extent, by the negative autocorrelation over larger distances.

Whereas free air and isostatic gravity is often equivalent in *continental* regression studies, isostatic gravity values are superior in *regional* comparisons; *e.g.*, Watts and Cochran (1974b) gave a good example for the necessity of eliminating the topographic effect which can distort the interpretation of Δg completely; this fact corroborates the use of isostatic anomalies.

5. Numerical Results

In evaluating Δg, the global part of gravity was only subtracted in form of an ellipsoidal normal potential; additional global trends have not been eliminated. In the computation of the isostatic corrections we did not take into account the

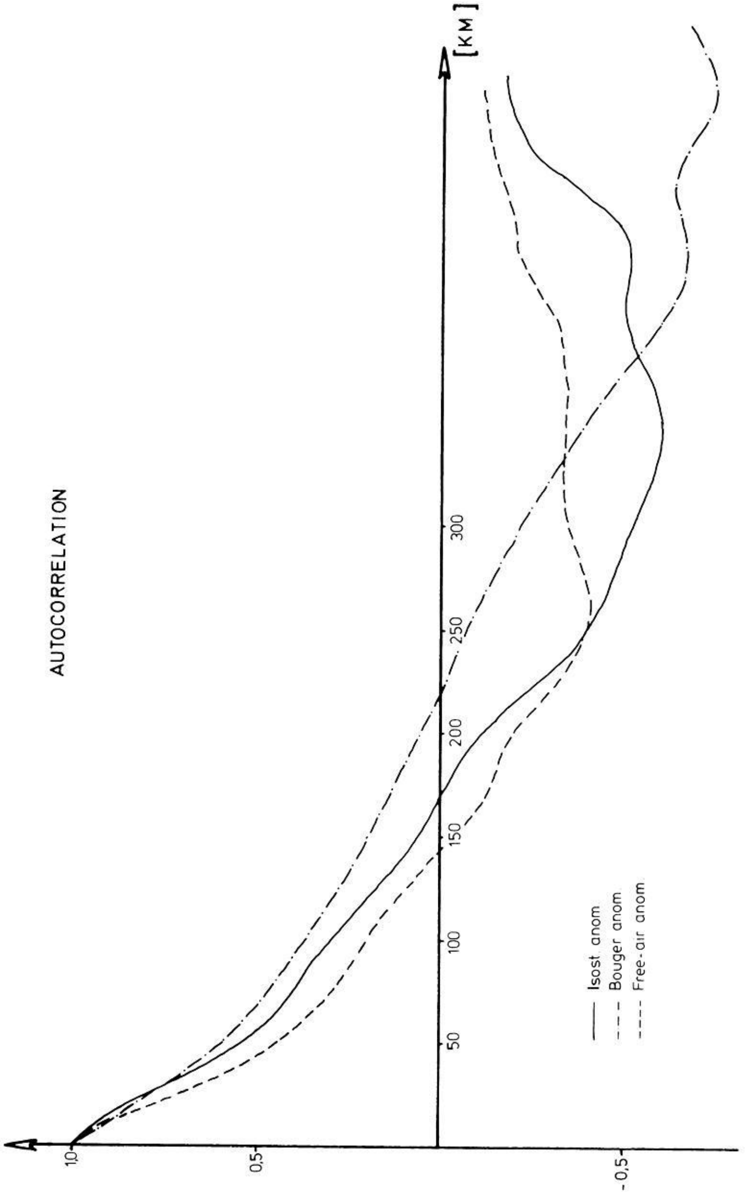

Fig. 3. Autocorrelation functions for mean anomalies (6′ by 10′ blocks) in Germany corresponding to flattening 1/297

global part of this correction, *i.e.* in evaluating the isostatic geoid height the isostatic corrections were, in general, completely ignored for the spherical distances $\psi > 5°$; within $\psi \leqq 5°$ they were everywhere taken into account within the F.R. Germany according to the model of Airy-Heiskanen mentioned before; outside Germany it was only applied in those areas where isostatic compensation really exists. This approach should be more realistic than a complete isostatic correction, including all oceanic areas, as in the Airy-Heiskanen concept. For mean anomalies of large blocks as used in the numerical integration of distant

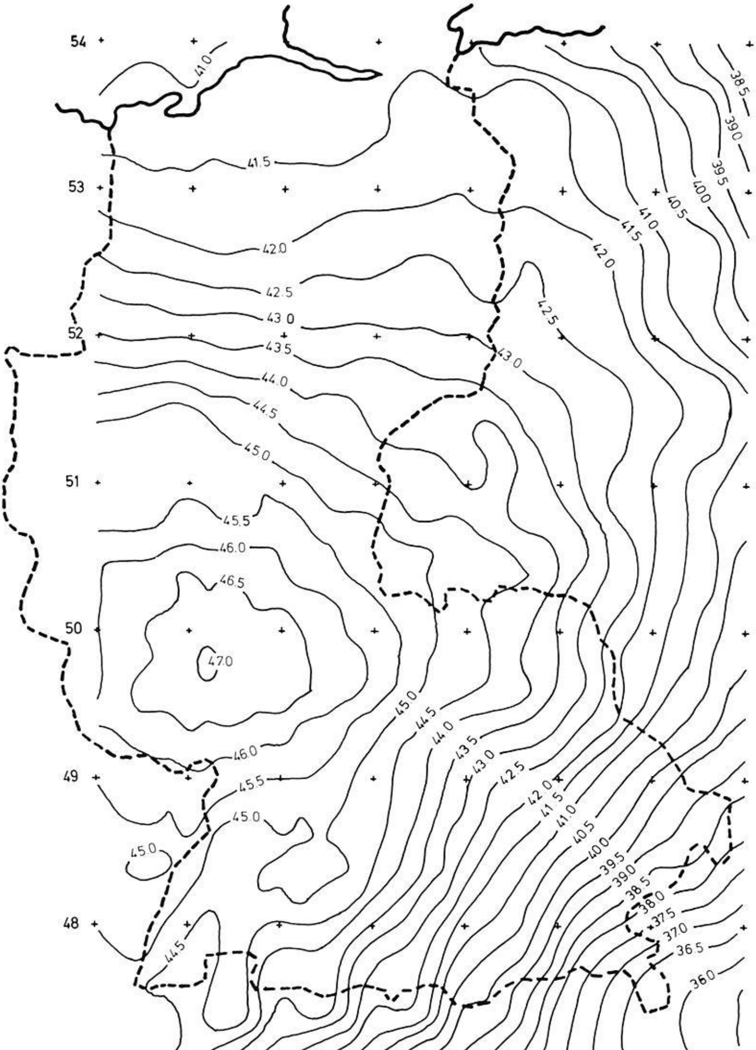

Fig. 4. Isostatic geoid of Germany for flattening 1/298.25; isolines (m) do not contain zero degree term $N_0 = -20$ m

zones in Stokes's formula the isostatic correction is, in any case, not very important. Figs. 4 and 5 show the isostatic geoid and the corresponding lateral distribution of density variations in the lithospheric model, respectively.

Fig. 6 shows the lateral density variations in the lithospheric model corresponding to free air anomalies. According to Eq. (10) the density variations are more dependent on topographic effects than the geoid undulations; when the variations in Fig. 6 are compared with those of the geoid in the same area (Groten and Rummel, 1974) the smoothness of geoid undulations in the northern part

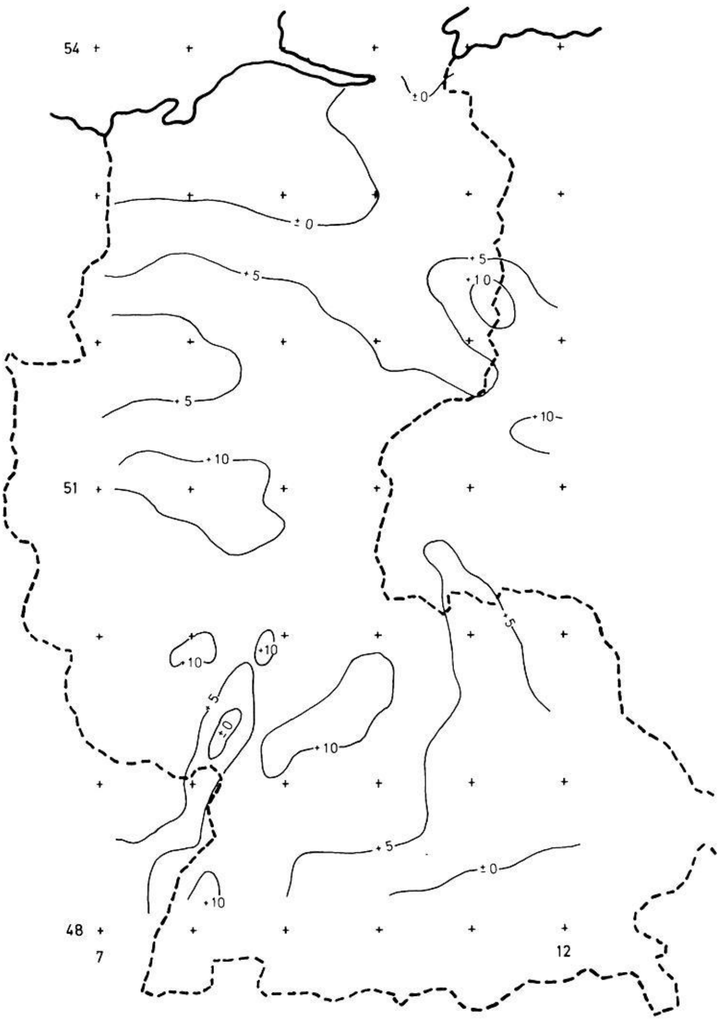

Fig. 5. Lateral density variations (10^{-3} gr/cm^3) in a lithospheric layer of thickness $H = 100$ km corresponding to isostatic anomalies of flattening 1/298.25 in F.R. Germany (for Airy-Heiskanen system with $D = 30$ km)

is in contrast to the detailed structure shown in Fig. 6. The smooth form of the geoid in Northern Germany is surprising and only a very small part of it is explained by lack of sufficient data in some parts of that area.

Let us consider now the correlation between heat flow and geoid undulations: A disadvantage of the results of regression analysis as shown in Figs. 7 to 11 is the lack of data. Therefore strict cross-covariance-analysis had to be replaced by simple regression studies.

Instead of the original heat flow data we used the results of trend analysis as found by Haenel (1971), Haenel and Zoth (1973) and Haenel (1974); in Figs. 8 to 10 they were used together with geoid heights in Europe as given by

Fig. 6. Lateral density variations (10^{-3} gr/cm^3) in a lithospheric layer of thickness $H = 100$ km corresponding to free air anomalies of flattening 1/298.25 in F.R. Germany

Marsh and Vincent (1974). Since the effect of the degree of approximation used in the analysis was remarkable the heat flow values of Haenel (1971) were used in Fig. 8 whereas in Figs. 9 and 10 the data from Haenel (1974) were applied. In Fig. 10 the effects of sedimentation and denudation have been taken into account. On comparing the data in Fig. 7 with those in Figs. 8 to 10 it is realized that there is, in general, only low regional (not local) regression of geoid height with heat flow whereas the *continental* regression is remarkable within the area of investigation. On inspecting details of the free air geoid it is seen that, *e.g.*, in Northern Germany and other areas where the data distribution was insufficient

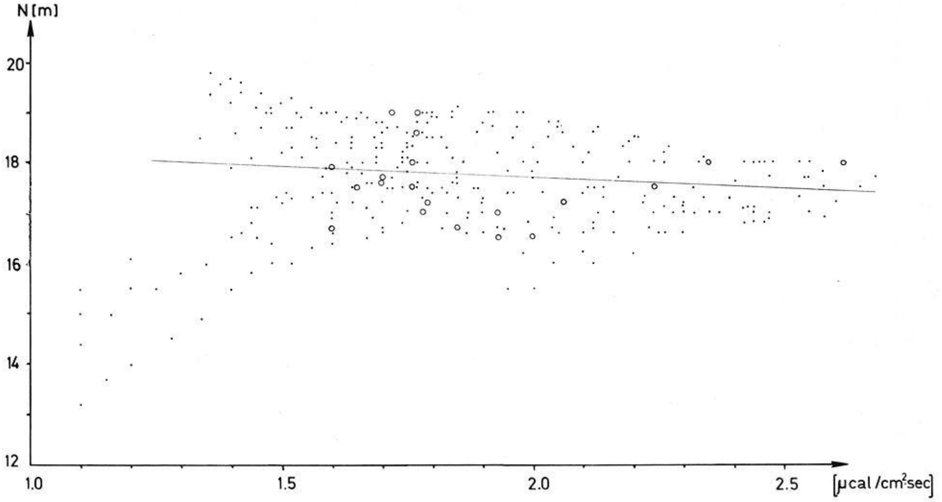

Fig. 7. Regression of (free air) geoid heights in Germany with heat flow values given by Haenel (1971) within $48° \leqq \phi \leqq 52°$ and $7° \leqq \lambda \leqq 12°$ (*E*) at 0.5° steps

there is apparently a better correlation than in the south where more heat flow data were available. The circles in Figs. 7 to 10 indicate multiple points where the radius is proportional to the number of points represented by the specific circle in the figure.

The meaning of the circles is the same in Fig. 11 where the relatively low regression of Moho depth with free air geoid heights is shown for Germany using the results by Giese *et al.* (1973); Moho depth again is defined as the depth of strongest velocity gradient in the interval 7.2 to 8.4 km/sec. The results are supported by the results of Liebscher (1964). Similarly low correlation is found between geoid heights and large-scale variation of mantle velocity as discussed by Giese and Stein (1971) and Giese *et al.* (1973).

On inspecting the above regression results in Figs. 7 and 11 we may ask for the sources of the regional geoid undulations. The geoid for Southern Germany is shown in Fig. 12 contoured in decimeter intervals. Small-scale variations are evident on this map and it is realized that even there the geoid heights vary only by a few decimeters. There might be local petrological sources of mean gravity anomalies as Kaula (1969) found for larger areas in global interpretation. Correlation of local anomalies with geological structures and Moho depth variations were pointed out, *e.g.*, by Plaumann and Dürbaum (1971) for Siegerland.

Two features of the detailed free air geoid are remarkable; (1) there is no strong anomaly in the area around Basel at the southern end of Rhine Graben; (2) in the "Hessischer Graben" *i.e.* the area around Kassel, north-east of the Rhine-Graben, where Giese *et al.* (1973) found a relative maximum of crustal thickness (in contrast to the relative minimum of crustal thickness in the Rhine-Graben) there is no deformation at all in the free air geoid; see also Groten and Rummel (1974) for an additional geoid section using other gravity data.

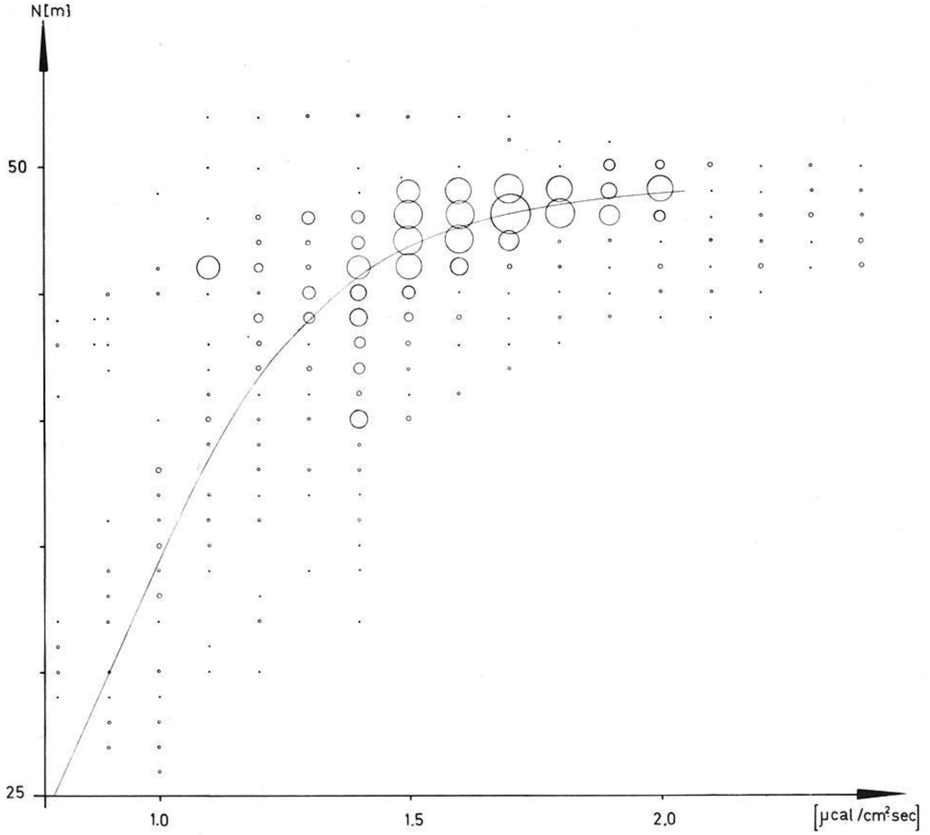

Fig. 8. Regression of (free air) geoid heights in Central Europe ($45° \leqq \phi \leqq 55°$ (N); $5° \leqq \lambda \leqq 25°$($E$)) with heat flow values given by Haenel and Zoth (1973); at 0.5° steps

It seems that such regional features are compensated completely. This assumption is in agreement with very strong *local* regression found in the regression analysis for local data having very different regression coefficients. On the whole, these coefficients might cancel each other in a *regional* survey such that for larger areas of regional extent no remarkable correlation is found. This holds for regression of gravity with crustal thickness, heat flow and other parameters. For instance in the area ($50.25° < \phi < 52.0°$; $9.5° < \lambda < 11.75°$) there is a remarkable negative regression of free air geoid heights with crustal depth which is compensated by a positive regression, *e.g.*, in Bavaria; heat flow in Northern Germany has positive regression with geoid heights in the eastern part and partly negative regression in the western part.

The results given by Woollard (1974) for 1° by 1°-blocks in the United States do not show the strong continental correlation between heat flow and the geoid as evident in Figs. 8 to 10 for central Europe. But a similar regional interdependence of several parameters as discussed above is visible also in Woollard's data. In

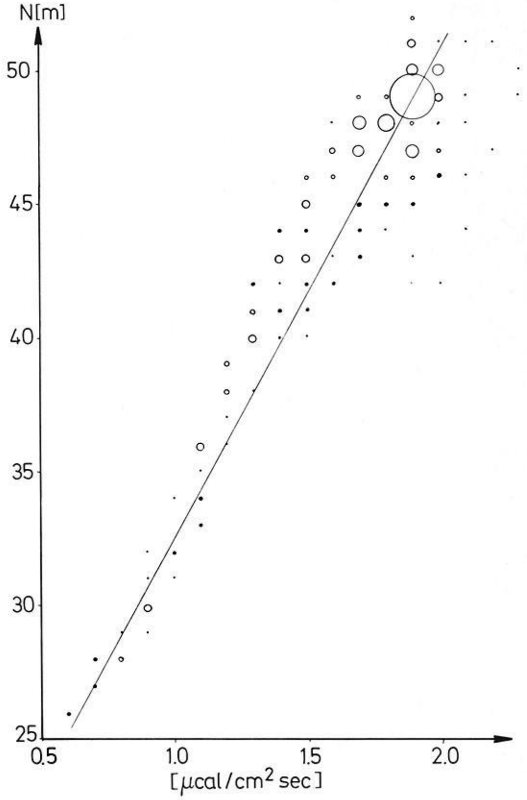

Fig. 9. Regression of (free air) geoid heights in Central Europe ($45° \leqq \phi \leqq 55°$ (N) and $5° \leqq \lambda \leqq 25°$ (E)) with heat flow values given by Haenel (1974); at 0.5° steps without corrections for denudation etc.

contrast to Woollard's results there is no remarkable correlation of mantle velocity and crustal thickness in Germany as is seen by comparing the results of explosion seismology by Giese *et al.* (1973).

On comparing the lithospherical density variations obtained in previous studies with our data it is realized that the lateral density variation models given by Figs. 5 and 6 reflect the velocity variations in Germany as shown by Giese *et al.* (1973). Because of lacking information on the thickness of the lithosphere and since radial density variations are ignored in these models they can, at present, give only crude approximations. This means that for representing *regional* features on continents like the present ones those models are more appropriate than in investigating *global* density distributions including those areas where slabs of lithosphere may locally descend to as much as 700 km depth. But whenever the lithospheric density variations and possibly flow in the asthenosphere are important single layer models seem to be appropriate, even if the thickness of the asthenosphere and the lithosphere are slightly varying. *E.g.*, a decreasing thickness of the asthenosphere as might be expected in central Europe along the north-south direction, *i.e.* towards the Baltic Shield, could yield positive linear regression of heat flow with N.

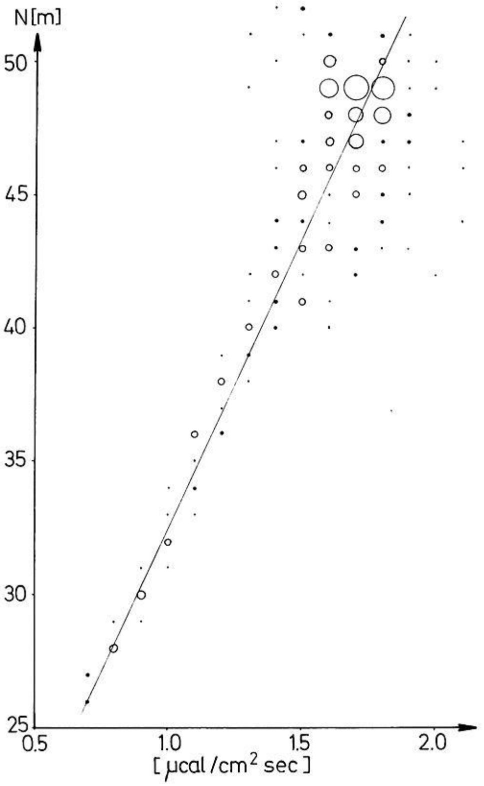

Fig. 10. Regression of (free air) geoid heights in Central Europe (45° ≦ ϕ ≦ 55° (N) and 5° ≦ λ ≦ 25°(E)) with heat flow values given by Haenel (1974) corrected for denudation etc.

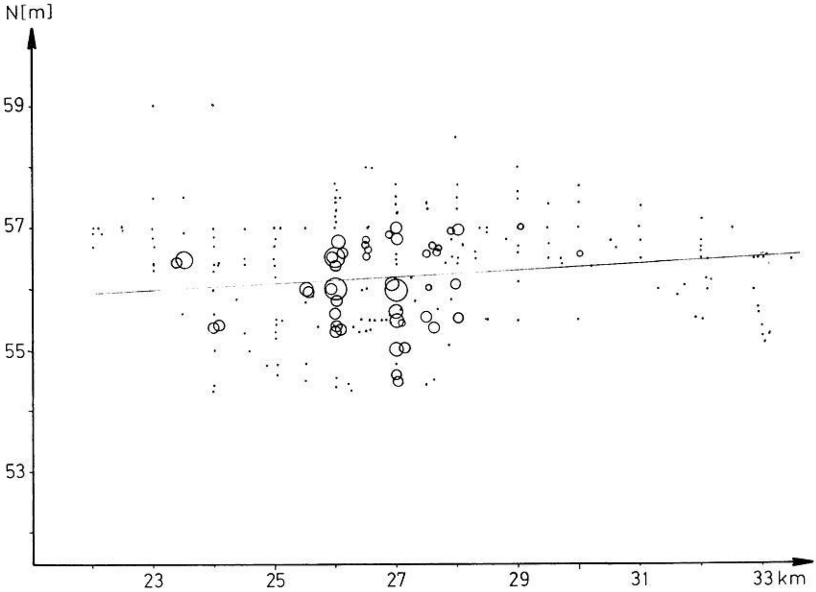

Fig. 11. Regression of Moho depth with geoid heights in Germany 47° ≦ ϕ ≦ 52 (N); 7° ≦ λ ≦ 12°(E); data taken at 0.5° steps

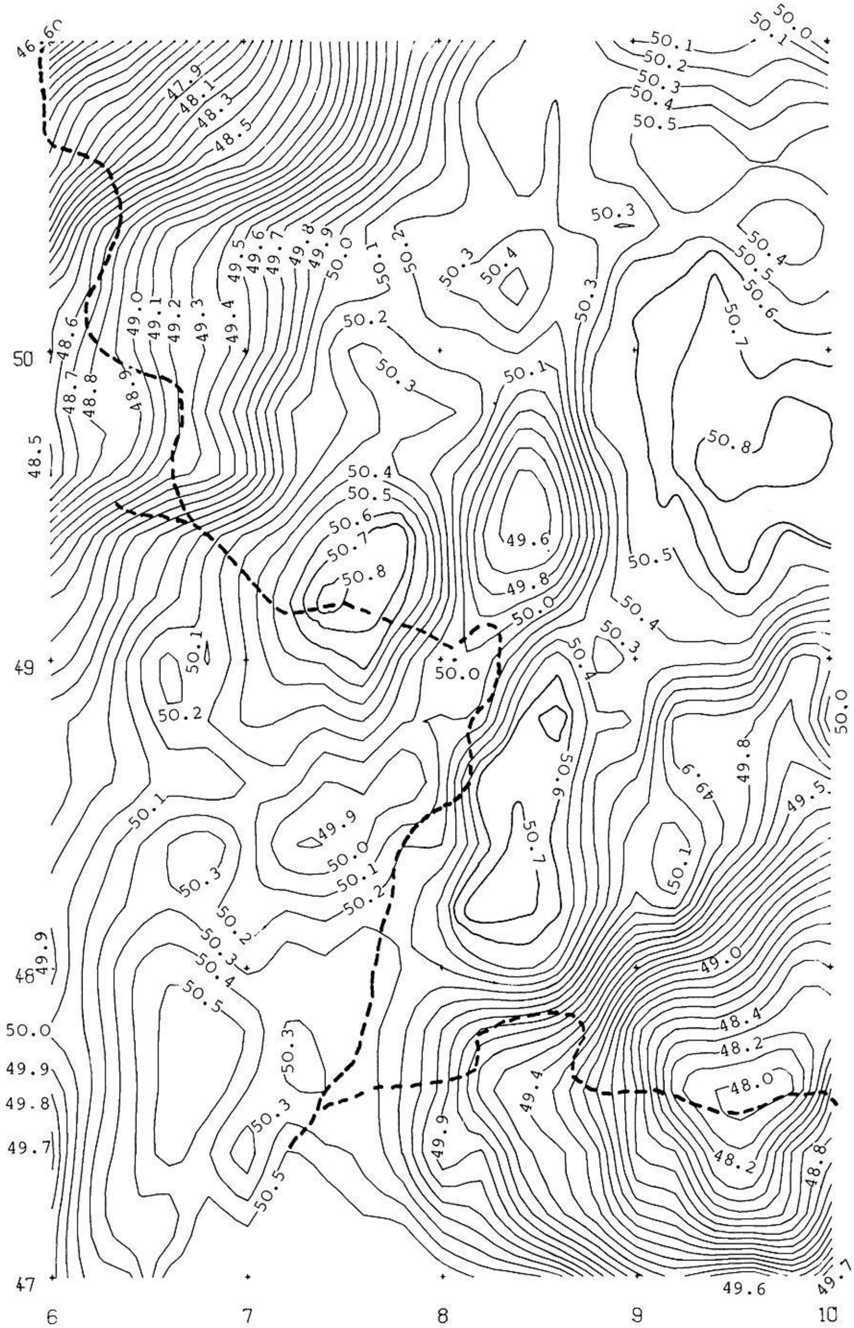

Fig. 12. Very detailed (free air) geoid of the Rhinegraben area for flattening 1/298.25. The broken lines indicate the political borders; N_0 is not included in heights (m) labelled to the isolines

6. Discussion

The Lower Harmonics Part. In Δg, N and μ' different parts of the spectrum are predominant as seen on inspecting Figs. 4, 5, 6 and 12. In any of these cases, the lower harmonics of degree $n < 17$ imply trends which are of remarkable interest, even in the regional interpretation. Therefore, the evaluation of the lower harmonics part is briefly discussed.

For several sets of GEM-coefficients as obtained from satellite orbit analysis together with mean surface anomalies of large blocks, differences which would basicly affect the analyses and results have not been found in the gravity harmonics $n \leqq 18$. For the flattening we used

$$f \doteq 1/298.25$$

instead of $f = 1/299.8$ as applied in other investigation as, *e.g.*, by Lambeck (1972). The reason is given by Groten and Rummel (1974).

On the other hand, the low harmonics can seriously affect especially the results of the regression analyses. But the explanation of the sources of the very low harmonics is still problematic. Even though there is probably no interrelation of gravity harmonics for $n \leqq 5$ with heat flow and similar data the low harmonics have not been eliminated from the gravity field used in the present regression analysis. This fact might cause uncertainties but it is difficult to clearly separate those gravity harmonics which could be produced deeply in the lower mantle (Groten, 1968) from those which might affect, *e.g.*, heat flow variations at the earth's surface.

If gravity harmonics for $n \leqq 5$ are produced by variations of the core-mantle boundary or even by an earth's core of slightly variable position (Egyed, 1964), it would be necessary to subtract the harmonics $n \leqq 5$ from the gravity field when regression with heat flow etc. is investigated. However in spite of the strong influence of low harmonics on linear regressions the number of harmonics to be subtracted is uncertain and on corresponding core-mantle models additional information is needed. Consequently, the well justified ellipsoidal normal potential as adopted at the IUGG General Assembly in Moscow 1971 according to Somigliana's theory has been used in the present investigation for evaluating Δg and N.

The residual zero degree term $N_0 = -20$ m in N has been taken from Groten (1974); it is only of secondary interest in our data. Therefore, it is not contained in the isolines of N as given in the above figures of the geoid. Consequently, whenever the geoid heights shown in the present paper are compared with other quantities in *absolute* terms then N_0 has to be added.

Regression of Gravity with Heat Flow. Most of the previous studies on the interrelation between gravity and heat flow have been considered either the very short period part of the spectrum or the low harmonics; so references were necessary in our case to the low harmonics part more than is usually done in regional investigation. A general problem in comparing the gravity field with regional heat flow distribution is the fact that gravity reflects the *present* density distribution whereas heat flow at the surface does not represent the present thermal field in the earth's interior. A special problem of the present investigation is the lack of data; in the area of Europe where relatively reliable gravity and heat flow data are available there is a remarkable linear trend of both fields in the north-south direction which, in case of the gravity field, is readily modified by simply subtracting different parts of the low harmonics.

On comparing Haenel's (1971, 1974) different heat flow maps with the one compiled by Stegena (1972) the influence of trends depending on the degree of trend analysis in heat flow data processing is evident. In the present study only Haenel's data have been used. Since local topographic effects are not supposed to be directly correlated with heat flow data only geoid heights were used in the regression analysis.

What makes the present study intricate in comparison to previous ones is the possibility of combined effects of convective and radioactive heat flow variations which can exist in the part of the spectrum under investigation.

On inspecting previous statistical investigations of *local* correlations of gravity with heat flow mainly radioactive heat sources have been considered. Moreover, correlation of heat flow with recent crustal movements on the one hand and correlation of free air gravity anomalies with land uplift on the other hand were found; *e.g.*, P. Vyskocil (1974) gave locally varying regression coefficients in Bohemia for the linear interrelation of crustal movements with heat flow. But the sources of both events cannot assumed to be situated in the gabbro layer because for the Moho to be a phase transition gabbro-eclogit a strong positive correlation of temperature gradients with Moho is necessary which has not been found; see, *e.g.*, (Kaula, 1968).

Buntebart (1973a, b), on the other hand, used Bouguer anomalies in his *model* investigations. Therefore, the question arises what type of gravity anomaly is best related to heat flow data. From our viewpoint, the isostatic anomaly is, in general, best suited because it is less dependent on local topography than other types of anomalies.

Studies of *global* correlation of gravity with heat flow and the interpretations have undergone many revisions since G.J.F. MacDonald, W.H.K. Lee and others started those investigation more than ten years aga (Lee, 1963; MacDonald, 1964; Lee and Uyeda, 1965). The main point was the physical explanation of positive and negative correlation. The question whether gravity is positively or negatively correlated with radiogenic and convective heat flow (McKenzie, 1967; Hagiwara 1971) has meanwhile found plausible explanations; Anderson *et al.* (1973) and others have pointed out that for *convective* heat transfer there is *always positive* correlation of gravity with heat flow for any Rayleigh-coefficient and any source of heat.

Conductive heat transfer was discussed, *e.g.*, by Magnitzkii (1963) and Lambeck (1972) where, however, in Magnitzkii's concept expansion due to temperature variations in any direction differs from Lambeck's concept of radial expansion. The correlation of the spreading rate along oceanic ridges with amplitude and wave lengths of mainly positive free air anomalies of the lower harmonics field $n \leqq 5$ is one of the common points in Lambeck's (1972) and also Anderson's *et al.* (1973) studies.

Kaula's global cross-correlation analysis (see Lee and Uyeda, 1965) of gravity with heat flow gave a slight *negative* correlation at zero degree. At first sight, negative correlation of gravity with heat produced by radioactive decay is straight forward unless mass transport is involved.

On the whole, the positive correlation along ocean ridges could be compensated by overwhelming negative correlation of conductive heat transfer in the oceans. Along ocean ridges the information which is obtained from free air anomalies is mainly due to boundary conditions as discussed, *e.g.*, by Kaula (1973). But corresponding results are not available in the present case and it is not quite clear to what extent the above results can lead to conclusions on the large-scale flow fields in the asthenosphere at central Europe. The simple inference of large-scale or even small-scale dynamic processes in the upper mantle from large-scale mass excess and possible flow in the oceanic part is certainly not justified. Heat transfer together with small-scale mass transport could be present in the Rhine Graben and in the Alps; large or small scale lateral mass transport might also be of interest in other areas of central Europe where it could explain the slight positive correlation of gravity with heat flow values.

Regression of Moho-Depth with Gravity. When the M-discontinuity is defined in the classical sense as the location of steepest gradient of velocity in the area of crust and upper mantle, *i.e.* for $7.2 \leqq v \leqq 8.4$ km/sec, a strong regression of Moho depth with Bouguer anomalies is expected; somewhat smaller regression coefficients are anticipated to exist, in general, for free air and isostatically reduced gravity with Moho depth. On inspecting the above given variances and correlations of Δg it is realized that each type of Δg can, in principle, be chosen for investigating crustal thickness H'; the choice depends on the specific influence of topography. But the various investigations of regional regression of free air anomalies with elevations h (see, *e.g.*, Vyskocil and Koziskova (1966) for small-scale, and Anderson *et al.* (1973) for large-scale studies) as well as the investigations of regional variations of H' (h), show clearly the problems still inherent in the prediction of H' from Δg. *E.g.*, isostatic Δg-values having small variances directly reflect the deviations from the specific crustal model as applied in the isostatic corrections and they are less dependent on topography than other types of Δg. Woollard (1959, 1966a, 1966b, 1970, 1972) and Woollard and Strange (1962) have done most extensive studies of regression of different parameters using free air, Bouguer and isostatic Δg whereas Wolf (1971) and several other authors used free air geoid undulations. Results as summarized by Woollard (1974) reveal general correlation between mean free air anomalies, regional, crustal velocities, mantle velocities, mantle depth and geological age; positive isostatic anomalies are supposed to yield too great Moho depth in comparison to reality whereas negative anomalies may lead to too low Moho depth. Some areas having deviations from isostatic equilibrium associated with positive isostatic anomalies and corresponding variations in H' (h) as well as some of the previous large-scale interpretations have to be revised in view of new lithospheric concepts as, *e.g.*, the correlation of positive and negative Δg with subsiding areas and land uplift. Part of those large-scale features could also be associated with horizontal temperature variations and flow in the asthenosphere as well as with relations between age and crustal thickness instead of geological sources which were previously supposed to be the reasons for gravity anomalies. For oceanic areas, *e.g.*, Kahle and Werner (1975) give such explanations for gravity regression with heat flow along continental boundaries. Horizontal temperature gradients below the lithosphere are only one further possibility for explaining the relatively strong continental regression of heat flow with gravity data.

7. Conclusions

The presently available data are only useful for rather general statements on the structure in central Europe. Regional variations in the gravity field can be explained by density variations in the upper mantle but presently available data do not give unique and detailed information of sufficient reliability. The mutual compensation of variations of different parameters leading to almost zero regression for regional variations of (1) gravity with Moho depth, (2) gravity with mantle velocity, (3) gravity with heat flow is typical. But especially for the maximum crustal depth in the "Hessischer Graben" no compensating variation of an other geophysical parameter has been found. The linear continental regression of gravity with heat flow could be an apparent one because of the uncertainties in the lower harmonics of gravity. With more data at hand, gravity could, in combination with heat flow and other data, yield additional information about such parameters as density in the upper mantle, especially in the lithosphere and asthenosphere and contribute to solutions of questions on lithospheric motion and asthenospherical flow as discussed by LePichon (1968), Isacks *et al.* (1968), Kaula (1973), Jacoby (1973a), McKenzie (1973), Press (1973) in central Europe.

In southern Germany where heat flow data are more reliable than in the north and vary more strongly, they are much better correlated with isostatic than with free air geoid undulations; this fact corroborates the perturbing influence of topographic effects in regional gravity – heat flow regression and the usefulness of isostatic reduction. The better the model applied in isostatic reduction the more efficient is the use of isostatic anomalies.

The averaging effect of formula (3) was found to be remarkable; small anomalies are completely eliminated. This is best realized by comparing single layer density variations with geoid undulations. Consequently, local regression of gravity with Moho depth etc. cannot be expected to become evident from geoids. But large scale regression should be better detected using geoid heights instead of gravity anomalies.

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