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Investigations on Vertical Crustal Movements in the Venezuelan Andes by Gravimetric Methods

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Abstract. A precise gravimetric network has been installed in the Venezuelan Andes to study eventual gravity changes due to vertical tectonic movements. The design and the measurements of the network are described and the accuracy is estimated.

In the center of the region a local gravity network has been reobserved three times. The detected variations are discussed.

In order to obtain a genuine statement as far as possible about the significance of observed gravity changes, requirements for the procedure of monitoring precise gravity networks are pointed out.

1. Introduction

The tectonic plate boundary between the Caribbean and the southern part of the American plate crosses Northwestern Venezuela following the course of the Venezuelan Andes (fig. 1). Horizontal movements in this area have been detected by geological methods along the Boconó Fault (Schubert and Sifontes, 1970), vertical movements being supposed in connection with the Andes' uplift.

As the total length of the considered zone is about 600 km with elevations from 100 m to 4000 m, it would hardly be possible to control vertical movements by use of levelling methods in a short time interval. Gravimetric observations, however, are capable of detecting height changes at reobserved points because of the dependence of gravity on elevation. This method has been used in several extended tectonic active regions (e.g. Torge and Drewes, 1977).

The problem is the conversion of gravity variations into height variations, which only can be done by knowledge of the actual vertical gravity gradient along the path of the moving masses. The determination of this value is somewhat problematic, but we can measure the local free air gradient as a rough estimation. In any case we obtain at least a qualitative estimation of vertical movements.

The advantage of the gravimetric survey is the easy and rapid performance and the almost invariable accuracy in respect to the distance between the points. Therefore the gravimetric method was chosen for monitoring the vertical component of the supposed movements in the Venezuelan Andes.

2. Regional gravimetric network

The precise gravimetric network consists of 58 stations and covers all the Venezuelan Andes in a length of about 600 km between the Colombian border (San Antonio) and the Caribbean Sea (Puerto Cabello). It has a width of about 100 km and is formed as it were three parallel profiles, one situated in the center of the Andes and one and one on each side of the mountains in the lowlands. One reference station is situated far off the network in Maracaibo (fig. 2).

The points are in general BMBM of the first order levelling net of Venezuela, that are concrete monuments with a 1m-foundation. Some stations are situated on foundation walls of churches. The net includes 11 stations of the National Gravity Network of Venezuela. The total range of gravity is 0.85 cm·s^{-2}.

In two sites of the investigation area, in Maracaibo and near Mérida, earth tides are recorded with an equipment of the Institute of Theoretical Geodesy of the University of Hannover / Germany (LaCoste and Romberg model G gravimeter, chart-recorder) in order to obtain actual parameters for the earth tide reduction.

3. Gravimetric measurements

The first gravimetric survey of the net was carried out in February / March 1978 using two LaCoste and Romberg model G gravimeters (no. 401 and no. 405). Totally there were performed 280 observations, each of those being the mean of three independent readings at one station. The instruments were carried by a station wagon.

The sequence of point observations had been planned before by a net optimisation, the target function for a free net adjustment being

$$m_p < 10 \cdot 10^{-8}\ \mathrm{m \cdot s^{-2}}. \qquad (1)$$

(m_p = a/v r.m.s.e. of point gravity values)

In conjunction with the present gravity network, another net around the Lake of Maracaibo was observed. This net was installed to detect gravity changes in the oilfields near the lake, which are due to the extraction of petroleum and related subsidences (Drewes, 1978). By means of the direct connection, a fusion of both nets is possible, covering in this manner a large region of the tectonic "Maracaibo-Block".

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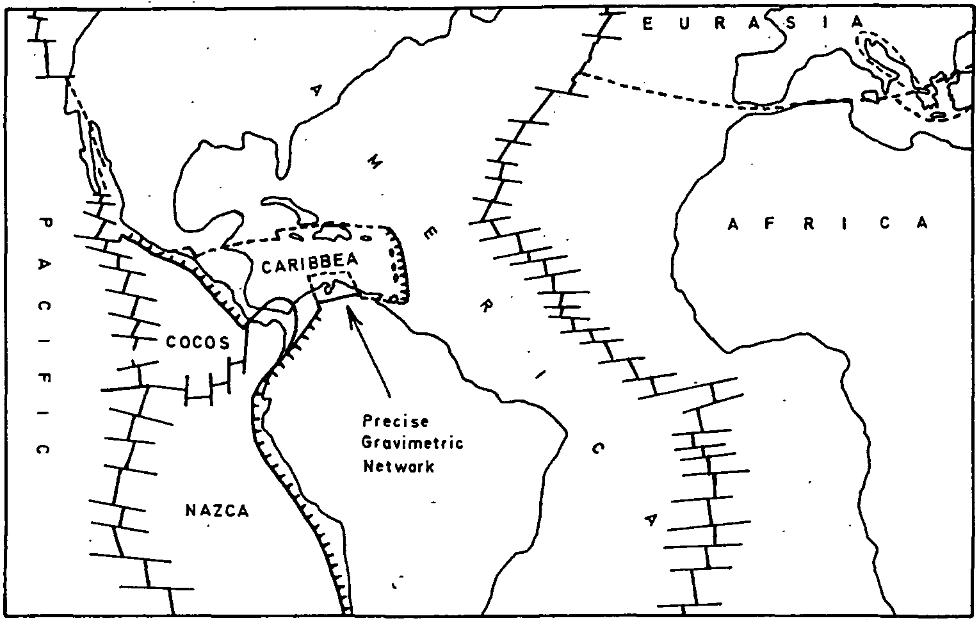

Fig. 1. Global Situation of the Precise Gravimetric Network

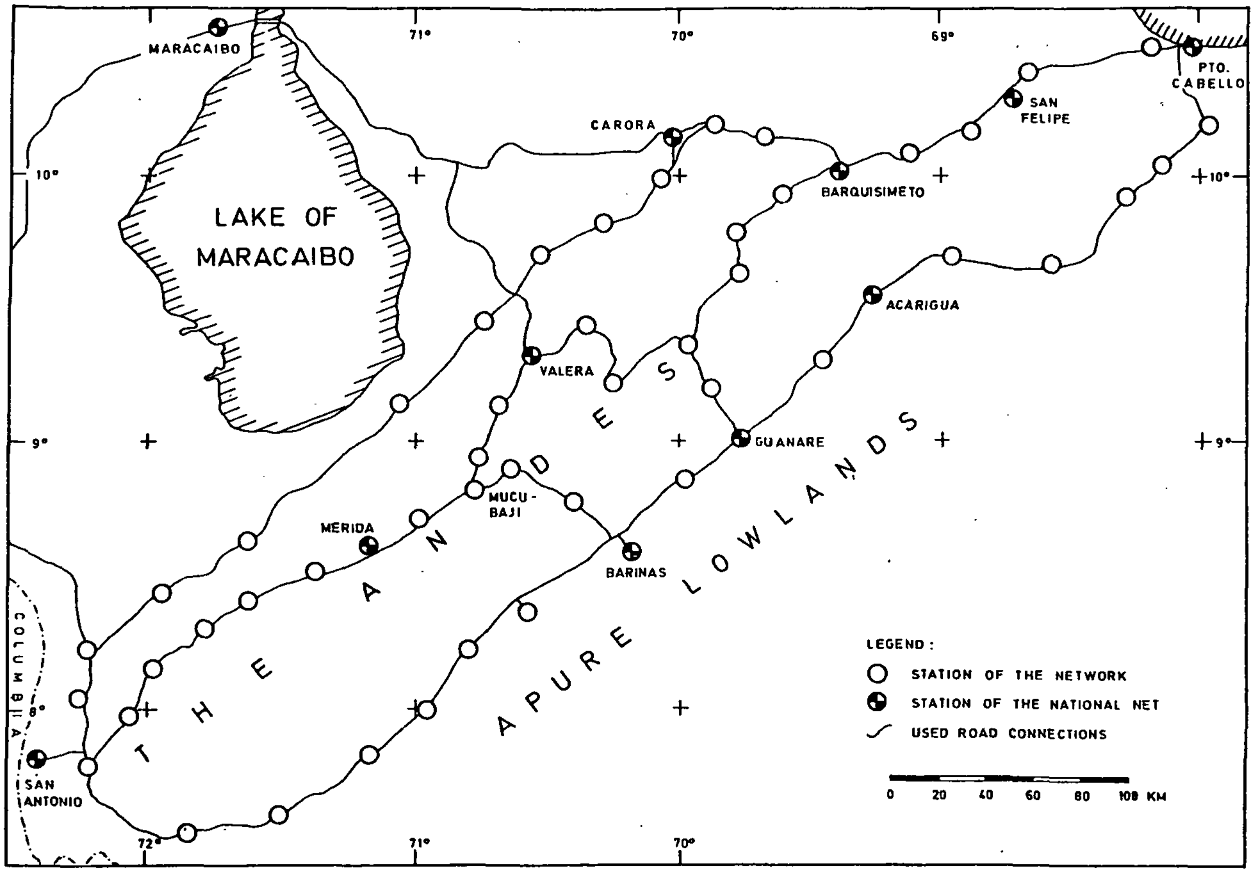

Fig.2. PRECISE GRAVIMETRIC NETWORK IN THE VENEZUELAN ANDES

4. Evaluation and results

After transformation of the readings into approximate mgal-scale (1 mgal = 10^{-5} $m\cdot s^{-2}$) by means of the manufacturer's tables, and the reduction because of earth tides by a modified Cartwright-Edden procedure with 505 partial tides (Wenzel, 1976), separate free net adjustments for each instrument have been calculated. The mathematical model for the adjustment of parameters is (Drewes, 1978, formula 14):

$$v_i = g_i - L_k - Y\cdot r_i - D\cdot t_i \mid p_i \qquad (2)$$

(g_i=gravity value of station i, L_k=gravity level of instrument at the begin of period k corresponding to reading 0.000, Y=scale factor, D= drift coefficient, r_i=transformed and reduced reading, t_i=time since begin of period k, p_i=weight of the observation).

As a result we obtain the r.m.s.e. of unit weight for both gravimeters:

$$m_o(401) = \pm 13\cdot10^{-8} m\cdot s^{-2}$$
$$m_o(405) = \pm 13\cdot10^{-8} m\cdot s^{-2}.$$

As there is no difference between the precision of the two instruments, all observations were introduced with an unit weight p=1 to a common adjustment, which also was calculated as a free net. Thereby the instrument no. 401 was fixed in its scale (Y=1). As a resulting r.m.s.e. of unit weight (now including also discrepancies between the gravimeters) we obtain

$$m_o = \pm 15\cdot10^{-8} m\cdot s^{-2}.$$

The average root mean square error of the point gravity values is

$$m_p = \pm\ 9\cdot10^{-8} m\cdot s^{-2},$$

fulfilling the condition (1) of optimisation. The results for the g-values of the adjustment are given in table 1.

The connection of the free network with a superior net, e.g. the National Gravity Network of Venezuela (RGNV) - in order to get an absolute orientation and scale for later comparisons - meets two principal problems:

1) The RGNV was observed in 1970 and adjusted within the Latin American Gravity Network (LAGN). In a readjustment, however, there were found gross errors of observations included in the former computation. The old and the new adjustment differ strongly.
2) As the time interval between the measurement of the RGNV and the present Andes' Network is 8 years, we cannot suppose constant gravity values. So we may not connect the present net to the gravity values of the RGNV 1970.

The main resulting crux is the determination of the actual scale factor of the instruments. The uncertainty of a roughly determined scale factor from the RGNV is

$$m_Y = \pm\ 6\ ..\ 7\cdot10^{-5}.$$

Related to the total range of the Andes' gravity network this produces an uncertainty of 50 .. $60\cdot10^{-8}$ $m\cdot s^{-2}$. This exceeds by far the internal precision of the net. The r.m.s.e. of the connected point values are also given in table 1.

5. Local network Mucubají

In the center of the Andes at Mucubají a small gravity network was installed to study local variations. The net is situated on both sides of the Boconó Fault, which in this region is defined by geologists within ±100 m uncertainty of position, and it is identical with a geodetic network of horizontal control (Schubert and Henneberg, 1975). Totally there are eight stations, all concrete monument with an 1 m x 1 m x 1 m foundation.

The mean topographic height of the net is about 3500 m, the mean gravity value 9.77360 $m\cdot s^{-2}$. The total gravity range is $18\cdot10^{-5}$ $m\cdot s^{-2}$. Because of this small difference in gravity the above mentioned problem of scale determination does not affect this network.

The first gravimetric observation took place in September 1977, the second in January 1978 and the third in August 1978. The same principle of readings and evaluation was used as described in sec. 3 and 4. The results of the free net adjustment are given in table 2, the relative gravity variations corresponding to the different periods are shown in fig. 3.

In addition to the measurements of the net, the vertical gradient of gravity has been observed in one reference station. The result is

$$\frac{dg}{dh} = 0.385\cdot10^{-5}\ s^{-2}.$$

At one side of the fault (north) we find no significant changes of gravity. The observed variations are always within the r.m.s.e. of determination. In the southern part, however, gravity changes exceed the threefold r.m.s.e. in several points. But there is no systematic in it. Therefore one should be careful interpreting those variations as tectonic movements. A great deal of local influences (ground-water etc.) should be considered.

To filter all the local effects from regional variations, an analysis of time series can be used (e.g. least squares prediction filtering). For this reason, however, a greater set of data in different epochs is necessary. The repetitions of gravity observations should therefore be

TABLE 1. Point Values and Errors of the Andes Gravity Network

Station Name	Gravity Value (mgal)	r.m.s.e. Free Net	r.m.s.e. National Net	Station Name	Gravity Value (mgal)	r.m.s.e. Free Net	r.m.s.e. National Net
Chinita	175.053	0.006	0.010	Chachopo	-439.728	0.009	0.030
Pto.Cab.	229.299	0.008	0.012	Mucubaji	-621.586	0.008	0.039
Moron	220.079	0.009	0.013	Las Pie.	-237.251	0.008	0.020
La Pica	196.232	0.009	0.013	Mucuruba	-417.334	0.008	0.028
S.Felipe	133.279	0.007	0.009	Mérida	-248.612	0.010	0.018
Chivacoa	98.002	0.009	0.011	Lagunil.	-162.673	0.009	0.016
Yaritag.	74.304	0.009	0.011	S.Cruz	-69.474	0.009	0.013
Barquis.	39.610	0.007	0.008	LaPlaya	-184.742	0.009	0.017
S.Pablo	19.210	0.009	0.011	LaGrita	-223.115	0.010	0.018
Pte.Tor.	86.170	0.009	0.011	M. Aura	-347.861	0.010	0.024
Carora	85.950	0.007	0.009	S.Crist.	-130.516	0.007	0.014
Sicarig.	63.917	0.009	0.011	S.Anton.	-57.097	0.009	0.011
El Empe.	28.146	0.009	0.011	Valencia	62.797	0.009	0.011
Valerita	69.827	0.008	0.010	Carabobo	65.583	0.009	0.011
Mendoza	32.231	0.008	0.010	Tinaqui.	90.555	0.009	0.011
Caja Se.	9.918	0.010	0.012	S.Carlos	121.069	0.009	0.011
ElVigia	-3.727	0.010	0.012	S.Rafael	120.028	0.009	0.011
Cano Am.	4.028	0.010	0.012	Acarigua	92.644	0.007	0.009
La Fria	10.244	0.009	0.012	Ospino	88.145	0.009	0.011
Colon	-92.116	0.007	0.013	Guanare	79.762	0.005	0.008
Quibor	12.282	0.009	0.012	Boconoi.	67.531	0.009	0.011
El Tocu.	26.332	0.009	0.011	Barinas	66.329	0.006	0.009
Guarico	-70.098	0.009	0.014	Barinit.	5.714	0.008	0.011
Biscucuy	28.235	0.007	0.010	Bolivia	44.105	0.009	0.011
Cimarro.	56.069	0.009	0.011	Socopo	15.743	0.009	0.011
Bocono	-118.134	0.007	0.014	Capitan.	31.803	0.009	0.011
Sta.Ana	-192.994	0.009	0.018	S.Barba.	35.110	0.007	0.010
Valera	-20.503	0.007	0.010	Abejales	24.822	0.009	0.011
La Puer.	-264.184	0.008	0.021	ElPinal	-30.645	0.009	0.012

Gravity Value (IGSN'71) of the Reference Station (Chinita) : 978160.12 mgal
Scale Factor (IGSN'71) of the Reference Gravimeter (401) : 1.0005±0.0001

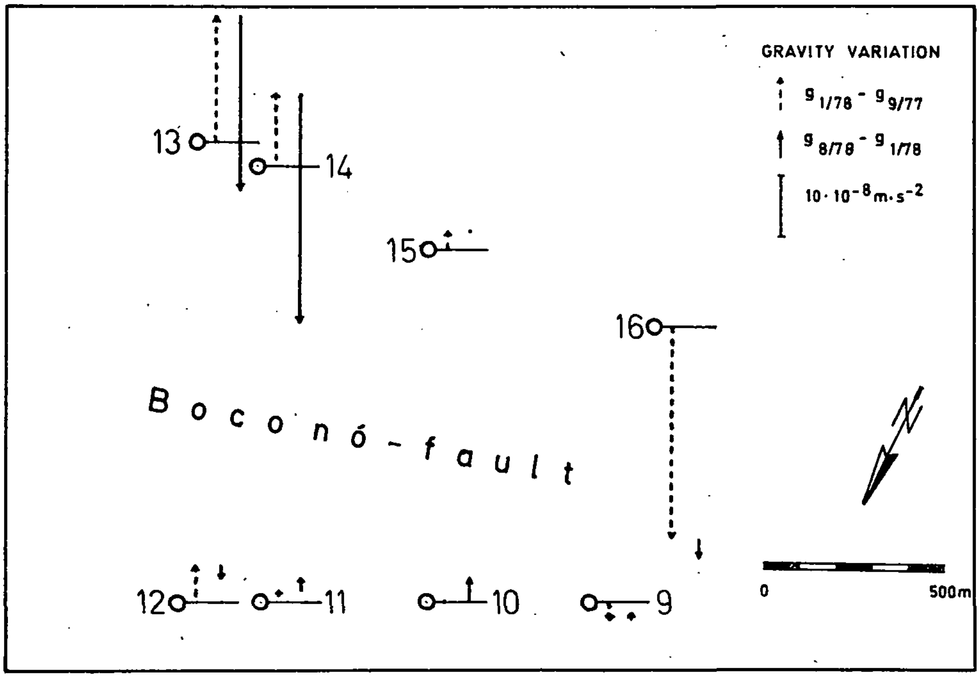

Fig. 3. Gravity Variations in the Gravimetric Network Mucubají

done in a short time interval.

6. Conclusions

From the analysis of the presented network we learn two principal requisites for the gravimetric control in geodynamics:

a) The internal precision of a network is often superposed by a greater uncertainty due to the insufficient determination of the scale factor. So, if we repeat the observations with another gravimeter, or if the scale factor of one gravimeter changes with time, we cannot compare the different epochs. The scale factor should therefore be determined externally with the same (or less) uncertainty as the determination of point values:

$$m_\gamma \leq \frac{m_P}{r_g} . \qquad (3)$$

(m_γ = r.m.s.e. of scale factor, m_P= a/v r.m.s.e. of point values in a free net adjustment, r_g=gravity range of net)

b) Observed gravity variations are often superposed by local effects. To eliminate these disturbances we need short period repetitions. Precise gravity networks for geodynamics should therefore be reobserved at least as soon as variations are observable, i.e. the gravity changes increase to the order of the uncertainty of determination:

$$\Delta T \leq \frac{m_P}{\Delta g} . \qquad (4)$$

(ΔT=time interval of observation, Δg= supposed or actual gravity variation)

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TABLE 2. Local Gravity Network Mucubaji

Station Name	Gravity (μgal, free net)		
	Sept. 77	Jan. 78	Aug. 78
Mucu 9	-2676 ± 10	-2679 ± 4	-2678 ± 7
Mucu 10	-1226 ± 10	-1226 ± 4	-1222 ± 6
Mucu 11	2671 ± 9	2673 ± 3	2675 ± 5
Mucu 12	7474 ± 11	7480 ± 4	7478 ± 7
Mucu 13	-3192 ± 11	-3171 ± 4	-3200 ± 7
Mucu 14	178 ± 14	190 ± 4	152 ± 7
Mucu 15	1787 ± 14	1790 ± 4	1790 ± 7
Mucu 16	-10370 ± 9	-10405 ± 4	-10408 ± 7

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