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GEOPHYSICAL CONTRIBUTIONS TO THE GEODYNAMICS OF THE EASTERN ALPS

by

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With 13 Figures

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1. Introduction

Geodynamic research activities of the Institut für Meteorologie und Geophysik (IMG) of the University Vienna and the Zentralanstalt für Meteorologie und Geodynamik (ZA) were concentrated onto the Alps and adjacent regions to solve various questions of geodynamics and plate tectonics.

They contribute to the knowledge of the structure of the lithosphere as well as of dynamic processes in the past and present. Methodical questions connected with these research objectives have also been investigated.

Geophysical measurements of areal type and along profiles investigated the structure of the underground on a regional scale. In selected areas local surveys were performed to determine the importance of features like faults for geodynamics and plate tectonics. Mainly refraction seismics, gravimetric and geomagnetic methods were used for these projects.

Paleomagnetism and isostatic investigations were the principal tools for studying geodynamic processes during the orogenesis of the Alps. Earthquake seismology, geodetic levelling and earth tide measurements supplied information concerning the recent geodynamic regime in the Alps.

Great emphasis was laid on the synoptic interpretation of data obtained by different geophysical methods. Theoretical investigations as well as instrumental tests experiments concerning measuring techniques have also been performed in order to improve geophysical techniques and to optimize the procedure of joint interpretation of different geophysical methods respectively.

Because many of these projects required considerable input of manpower, instruments and financial support several investigations were executed in cooperation with other Austrian and foreign geophysical institutions.

2. Regional structural investigations

The determination of the size and the physical characteristics of the rigid plate formed by the crust and the uppermost mantle — known as the lithosphere in terms of plate tectonics — and the underlying weaker layer of the asthenosphere is a major goal for investigating the dynamics of the earth.

In addition the regional structure of the crust can be seen as the result of various geodynamic processes during the Alpine orogenesis. Therefore the knowledge of these structures is a valuable instrument for decovering the geodynamics of the Alps.

2.1 The international seismic experiments ALP 75, ALP 77 and ALP 78 (Publications 3, 62, 90)

Various refraction seismic profiles have greatly enhanced our knowledge of the structure of the crust beneath the Alps during the last decades. However, the coverage of the Alps with seismic profiles was not at all uniform, because most of the profiles in the post had been situated in the Western Alps. In addition, these profiles were oriented preferably perpendicular to the strike of the dominating geological features. With the aid of new powerful interpretational methods like ray tracing procedures it became evident at the beginning of IGP that an unequivocal interpretation of these old profiles is not possible. Because of the wide spacing of profiles and stationsit is not possible to distinguish between lateral and vertical velocity variations. This led to the concept of longitudinal profiles, which are oriented parallel with the strike of the main geologic units of the Alps. Thus one is avoiding strong lateral velocity gradients. As the whole length of the Alps is covered by the refraction line, this allows deeper penetration than on short transverse profiles: information on the structure of the lower lithosphere beneath the crust can be obtained as well. The knowledge of the structure at that depth range should give an essential contribution to the understanding of the geodynamic evolution of the Alps and allows very interesting comparisons with the structures beneath older orogens.

The first Alpine Longitudinal Profile (ALP 75) was carried out in 1975 in international cooperation of institutes from Austria, Federal Republic of Germany, France, Great Britain, Hungary, Italy, Switzerland and Yugoslavia with a total of approximately 200 scientists participating.

Starting at the western end at Mont Revard, France the profile follows the strike of the Western Alps in north-easterly direction up to the Wattener Lizum (Torsee) south of Innsbruck. There it turns almost to the East in order to follow the strike of the Eastern Alps and terminates at Körmend, Hungary. In addition to the main line which is 850 km in length and which rather precisely follows the axis of the negative gravity anomaly several shorter profile segments were observed like Judenburg (Lavantsee)-Deutsch Altenburg, Hochfilzen-Kirchberg a. d. P., Hochkönig-Kötschach, Wattener Lizum-Eschenlohe etc. The longest part of these profiles runs through Austria and contains 4 shot points. Two of them had been placed on the bottom of mountain lakes (shot point Dilake Torsee, Wattener Lizum and shot point E. lake Lavantsee, Judenburg with depths of 6 and 12 meters respectively). To get sufficient seismic energy transmission into the ground, an advanced blast technology had to be developed by distributing the total charge of 1,2 — 2,5 t over a large area of the lake bottom in a carefully dimensioned grid pattern. The generated P-waves reached vibration velocities of 4 cm/s with frequencies of 4—40 Hz at the lake shore and could be recorded along the profile at distances of at least 500 km [3].

In addition at the shotpoint E reflection seismic observations have been carried out in cooperation with the Institut für Erdölgeologie und Angewandte Geophysik, Mining University Leoben. With two 24-trace seismic instruments a reflection profile of approximately 1,5 km length was layed out. Astonishingly clear signals of deep reflections with travel times of 11—12 seconds were recorded although the geology of this area is complex and due to numerous faults high attenuation and multiple reflections as well as complicated refractions have to be expected.

After the severe Friuli earthquakes of May and September 1976 it was decided to arrange additional seismic longitudinal profiles covering the earthquake region. In 1977 a profile extending from Mt. Caninin in the East via Tolmezzo and Salurn to the Sondrio region approximately parallel to ALP 75 was recorded which is known as ALP 77. Further three profiles forming a trident were observed as ALP 78. The central shot point was the lake Obersee at the Stallersattel (Defreggen valley/Eastern Tyrol). The three profile segments were Obersee-Trieste, Obersee-Spielfeld and Obersee-Eschenlohe.

2.2 Seismic profiles (Publications 59, 80, 81, 91)

Using the high seismic activity in northern Italy after the Friuli Earthquakes the project SNEALP (Seismic Network EasternAlpes) has been performed in cooperation with the University of Birmingham. For this project the Friulian aftershocks were observed for a three months period like refraction shots by seismic stations grouped as a profile. The recording stations were situated in Gnesau, Gurk, Stolzalpe, Unzmarkt and Judenburg [59].

In addition the IMG participated in other refraction seismic surveys in Europe during the IGP which were organized by German, Czechoslovakian and Hungarian institutions. Especially the profiles Villach-Eferding-CSSR, Rheinisches Schiefergebirge-France and the Scandinavian long range profile have to be mentioned. The purpose of this participation is to obtain results, which can be compared with Alpine data. While all these profiles as well as the ALP-experiments were investigated by specially designed seismic blasts, shorter profiles up to a length of 70 km were observed by using regular quarry blasts. From the quarries in Froiach and Klaus observations along the profile Linz-Klagenfurt have been carried out in three segments.

Unfortunately in quarry blasts usually the delay technique is used. Therefore it was necessary to study the energy transmission of such delayblasts in detail [80]. This revealed considerable differences in the seismic efficiency of various blasting techniques and showed that different mechanisms exist for causing seismic vibrations in connection with the breakage of rock. Usually the breakage of rocks is performed by the primary shock-wave and secondary tensile loosening. By using a special blast geometry rock breakage can be obtained also by a shear stress mechanism [81]. Also the parameters involved in the propagation of vibrational energy have been discussed [91].

2.3 Seismic models of the Alpine crust (Publications 63, 4, 52, 16, 50)

As a result of the previously described seismic profiles and especially the ALP experiments a detailed crustal model was obtained.

In the Central Alps a troughlike thickening of the earth's crust of approximately 50 km exists, which becomes stepwise thinner towards the East [63]. Whereas in the Pannonian Basin the thickness of the crust is only 27 km.

At a depth of 20 km there is a continuous inversion zone, i. e. a zone of decreased propagation velocity which can be considered as an area either of decreased rigidiy or of abnormal high temperature. In terms of classical earthquake seismology this discontinuity is named after the Austrian geophysicist Conrad Discontinuity, although the original interpretation of this discontinuity was that of an abrupt velocity increase from about 6,2 to 6,8 km/s. An additional inversion zone in the upper crust seems to exist within the Alps at the depth of 8 to 12 km [4]. This inversion zone is traceable as far as 80 km east of Judenburg. A relation to known fault systems and geological structures has not been detected. The disappearance of this upper inversion zone and the special details of the ALP-results in the area of the eastern margin of the Alps point to a complex structure of this transition area.

The complex pattern of seismograms at the eastern end of the Alps can be interpreted only by two-dimensional velocity models, i. e. velocity distributions, being variable in the vertical direction as well as in the horizontal [52]. With the aid of a modeling program allowing the calculation of seismic travel times for arbitrary two-dimensional velocity-distributions it was possible to construct models of the Eastern Alpine margin [16]. However the compatibility with gravity data has not been proved yet. The preliminary model is presented in figure 1. It shows the distribution of the propagation velocities between the shot points E and F Körmend (Hungary) which has been derived by evaluating the refraction seismograms of shotpoint E, with this method. Fig. 2 shows the same profile evaluated for the reverse shot (shotpoint F,). This latter model agrees very well with the seismograms of both shotpoints. It has been derived from the model of fig. 1 by slight modifications of the shape of the inversion zones.

The above mentioned program was also used to test the model for the crustal structure of the Eastern Alps, published by different authors. It shows that the wave groups, which earlier were interpreted as being reflected through alternating layers with velocity inversions can also be interpreted as waves which run in one single channel in a zig-zag path. As a result of this a substantially simplified model of the lower crust is obtained.

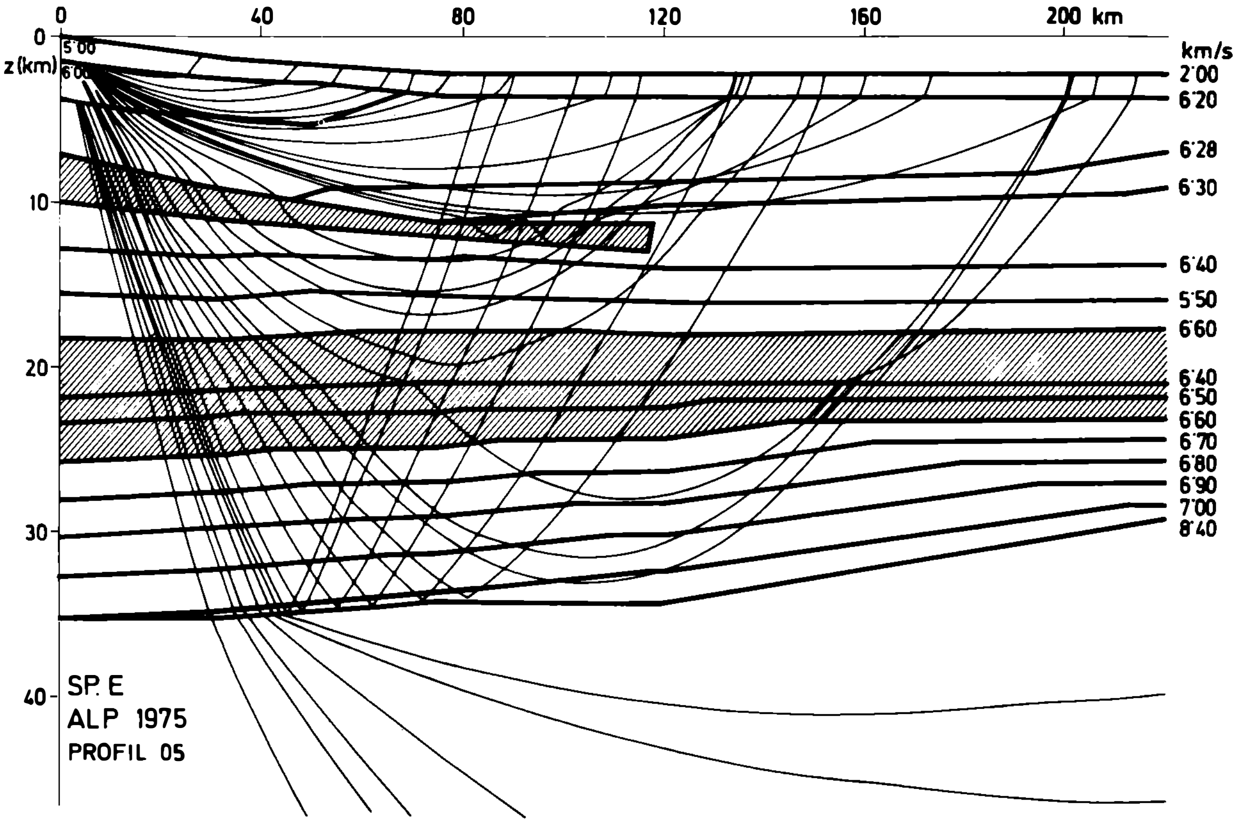

Fig. 1: Model cross section of ALP 75 profile between shot points E and F. The P-velocity distribution of the model has been derived from the seismogram of shotpoint E at lake Lavantsee (14⁰ 34' 21" E, 47⁰ 03' 34" N) near Judenburg by the ray tracing method.

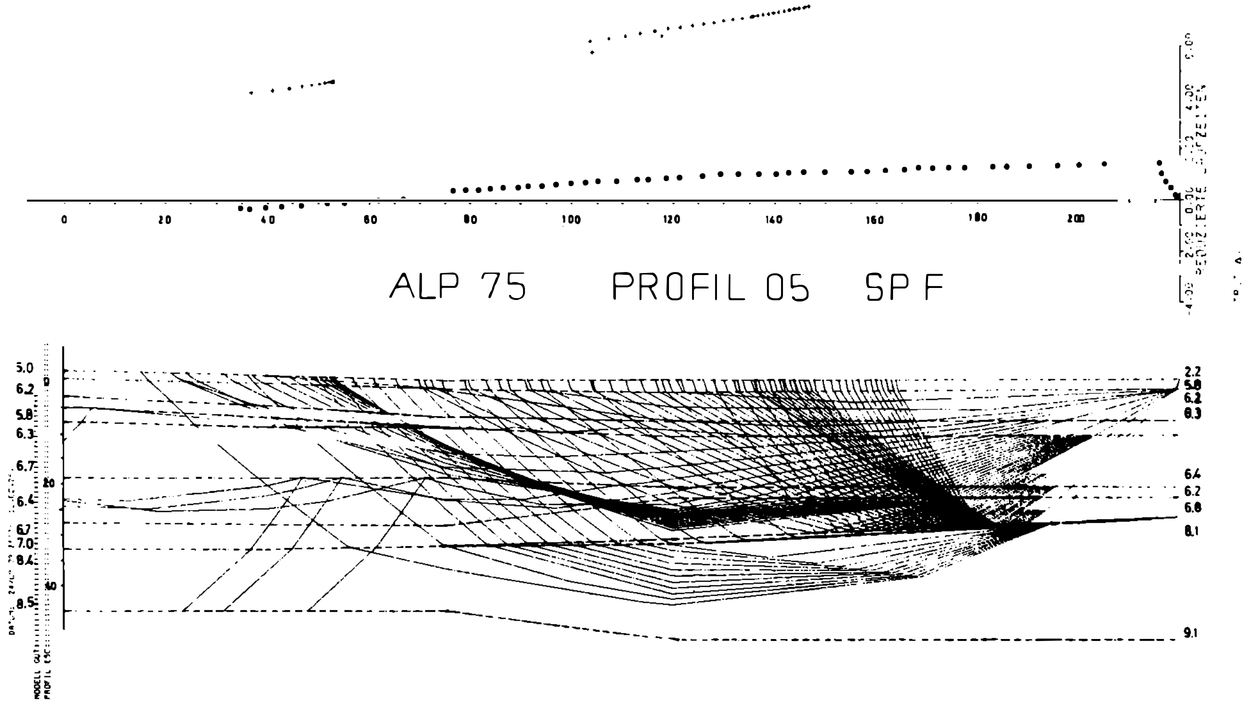

Fig. 2: Model cross section of ALP 75 profile between shot points E and F. The P-velocity distribution of the model has been derived from the seismogram of shotpoint F at Körmend (17⁰ 01' 04" E, 47⁰ 07' 17" N) by the ray tracing method.

2.4 The Periadriatic Lineament (Publications 87, 77, 43, 78, 71)

The Periadriatic Lineament is a very interesting feature of the geology of the Alps which separates the Southern Alps from the Eastern Alps. However the real importance of this feature is still unknown and there are views seeing it as negligeable as well as theories which credit the lineament regional or even continental importance.

Therefore extensive geophysical investigations with different methods have been carried out in the eastern part of the Lineament. Gravimetric and magnetic measurements locally, complemented by refraction seismics and geoelectrics, were performed between the Austro-Yugoslavian border in the South and the line Villach-Wörther See-Völkermarkt-Bleiburg in the North thus covering the mountain chains of the Karawanken and its foreland.

The geology of this area is characterized by crystalline rocks in the North which dips southward. There they are covered by the conglomerates of the Sattnitz in the southward direction. These conglomerates are overthrusted by the calcareous Northern Karawanken in the South. Next the lineament zone and then the Southern Karawanken follow.

Gravity measurements have been carried out in the entire area described above. An aereal distribution of gravity stations has been achieved despite the extremely mountainous character of the region. Together with gravity data provided by the ÖMV-AG (Austrian Mineral Oil Corp.) a total of 795 gravity observations have been carried out within approximately 1500 km². A Bouguer gravity map has been constructed with this data (see Fig. 3). The main feature in this map is a gravity trough along the northern flank of the Karawanken which strikes East-West. Only in the western part the trough bends to a WNW direction thus tending to the Mölltalfault. In the northern slope of the trough secondary gravity minima are formed in the districts of Sabalahöhe, Rottenstein and Eberndorf. North of this trough one east-west striking gravity high extends from the Pyramidenkogel to Klagenfurt. The southern slope of the trough is characterized by a disturbed pattern of isolines in the region of the Periadriatic Lineament, probably caused by locally occuring volcanites and other rocks of higher density. The main features of the Bouguer gravity map have been interpreted by two-dimensional models. The trough in the gravity map is explained by the low density of the Sattnitz-conglomerates, which forms a wedge between the crystalline rocks and the calcareous formations of the Karawanken having higher densities. The conglomerates end approximately below the ridge of the northern Karawanken in depths of approximately 1000 m. Fig. 4 represents model cross sections at the Obir [87].

Probably the margin of the southward dip of the crystalline has to be interpreted as a fault, which extends mainly along the Rosental. The northern flank of the gravimetric trough corresponds to this Rosental fault and the southern most part of the southern flank is associated with the Periadriatic Lineament. This seems to indicate that both features have to be seen geologically in context with one another.

Further it is of interest that the Karawanken show no gravimetric indication of a mountain root which has to be expected for an independent mountain range with isostatic behaviour [77].

Detailed refraction seismic and geoelectric measurements investigated the structure of the conglomerates in the area Plöschenberg-Köttmannsdorf and could trace the southward dipping crystalline rocks underneath the overlying conglomerate. The measurements yield representative values of propagation velocities and the subsurface topography of the crystalline basement below the sediments [43]. P-velocities measured at the surface of the crystalline rocks (4350 m/s) are low in comparison to limestone or fresh crystalline formations.

Also magnetic measurements were carried out along the Lineament and in the Karawanken [78]. At approximately 3800 stations the geomagnetic total intensity (T) was measured with proton magnetometers. The area

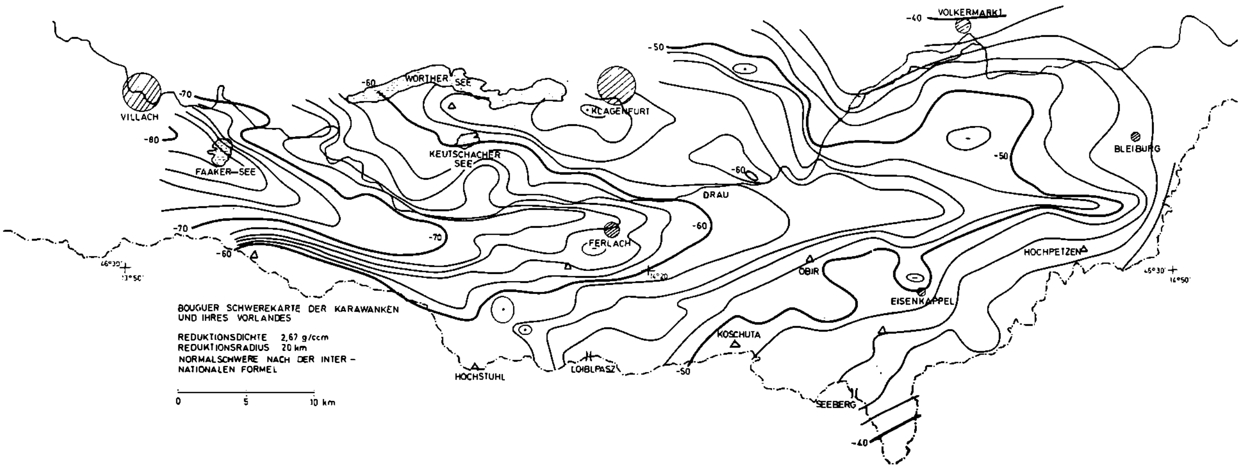

Fig. 3: Map of Bouguer-Anomalies of the Karawanken and their northern foreland [87].

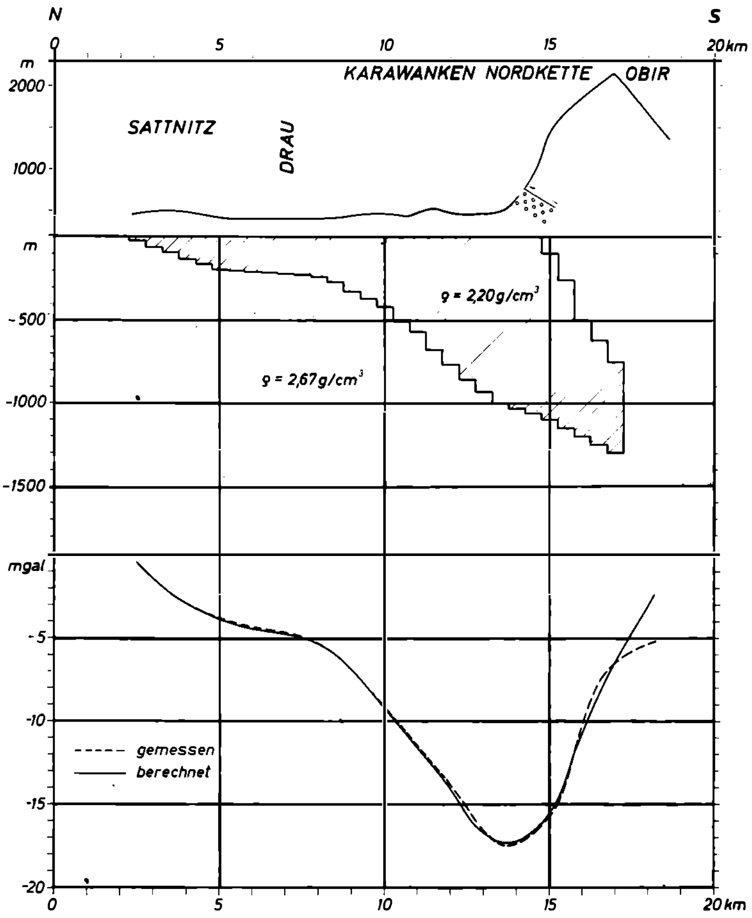

Fig. 4: Results of the gravimetric survey in the Karawanken top: topography on N-S profiles (the overthrust of the Karawanken over the conglomerates is indicated); centre: two-dimensional gravity models (density contrast: — 0,47 g/cm^3); bottom: comparison of observed and model gravity anomalies.

under investigation was 860 km^2 in size. All measurements were reduced to the epoch 1975.0. The rather large height variations necessitated an altitude correction in using the vertical gradient of T ($\sim$22 nT km^{-1}). The main field was calculated with a least square second order polynomial fit in order to determine the residual field ($\triangle$T).

In the investigated area three different zones of magnetic anomalies have been observed. The southernmost zone is characterized by long and narrow anomalies. In the north-western part of the investigated area a broad zone of short and mainly negative anomalies exists. In the North East an extensive positive anomaly is situated.

The first zone is correlated to the Periadriatic Lineament. In the west the anomalies are tied to lamellae of tonalitegneisses. The pattern of anomalies indicate that these lamellae have a greater extension than local outcrops suggested. The greatest anomalies have been observed along the eastern part of the Lineament. They are connected to the diabase of Eisenkappel. Two-dimensional model calculations reveal diabase dimensions of 300 m in width and a depth range of approximately 700 m, dipping steeply to the south. To obtain a good fit between the model calculations and the observed data the rather small inclination of I = 25° had to be used. This indicates either a tilt of the diabase by tectonic forces or a dominant remanent magnetization gained in low magnetic latitudes. In this context it is also interesting that in the carboniferous rocks at Nötsch also very small inclination values have been observed thus indicating a former position in low geomagnetic latitudes (Heinz, personal communication, 1979).

The second zone of anomalies in the northwestern part of the investigated area is limited in the south by the southern rim of the Sattnitz thus indicating that this rim marks a major fault zone.

A broad and elongated anomaly with an amplitude of approximately 30 nT constitutes the third zone. Its strike length is at least 35 km. According to two-dimensional model calculation the anomaly can be explained by crystalline rocks dipping under the northern chain of the Karawanken. It seems that this dip is increasing to the south while approaching the Lineament. Beneath the Drau-valley the crystalline formations are in a depth of 300 m to 400 m.

For performing these model calculations systematic in situ measurements of susceptibility of rocks have been carried out in the entire area. With the exception of the diabase of Eisenkappel the susceptibility shows only small but systematic variations [71].

The magnetic map of southern Carinthia was also interpreted qualitatively with regard to faults and other tectonic features. Two main faultdirections can be proved: The first is parallel to the Periadriatic Lineament, whereas the other one strikes SSW-NNE.

Finally it has to be pointed out that the geomagnetic model calculations are in accordance with the gravimetric ones, both showing a uniform picture of the northern part of thc Periadriatic Lineament.

2.5 Geomagnetic survey of Austria (Publications 65, 70, 69, 56, 53, 54)

The geomagnetic survey of Austria has been revised and updated for the epoch 1975.0. The aim was to get a better idea about the main field in the Eastern Alpine area and to pick up large scale geomagnetic anomalies, which could be correlated with the Alpine orogenesis [65; 70].

This investigation is based upon observations of D, H, and Z at 227 stations.

In the residual maps two large anomalies, the Berchtesgaden anomaly and the Moravian anomaly, can be recognized. Only parts of both anomalies are situated on Austrian territory. Most likely these anomalies are caused by magnetized bodies in the upper crust between 10 km and 20 km below surface. As their strike-direction is almost parallel with the axis of Alpine-Carpathic orogene both anomalies have to be considered as an overall geophysical feature of the Alpine-type mountain system.

On the eastern rim of the Tauern Window at a number of stations the total intensity of the earth's magnetic field was observed. Aditionally, at selected sites in-situ measurements of the rock susceptibilities were carried out [69].

It is evident that in an area like the Alps, where often rather inaccessible regions occur, airborne measurements could speed up the survey considerably. Therefore the IMG tried to perform an aeromagnetic survey at least in the central and northwestern parts of the Eeastern Alps. It soon became evident that this project by far exceeded the frame of the national program for the IGP. Consequently soon after the start of preparations for these investigations the aeromagnetic survey was seperated from the IGP-project and installed as an own national project. Nevertheless, the aeromagnetic investigation of the Alps is of great importance for geodynamics too. Fig. 5 shows the aeromagnetic map of Western Austria. Magnetic anomalies are concentrated in the regions west and east of the Unterengadin-window, in the western part as well as in the centre of the Tauern-window, in the area south of Kufstein and in the western part of Graywacke-zone. A dominating feature of this aeromagnetic map is the wellknown Berchtesgaden anomaly.

Of great geodynamic interest are the anomalies in the area of Matrei, geologically connected with the upper schist cover. These anomalies seem to indicate that the causing ultrabasites are fairly deep-rooted and this affects the importance of the Matrei-zone for the geodynamic evolution of the Eastern Alps. It will be necessary to test this hypothesis by model calculations [56].

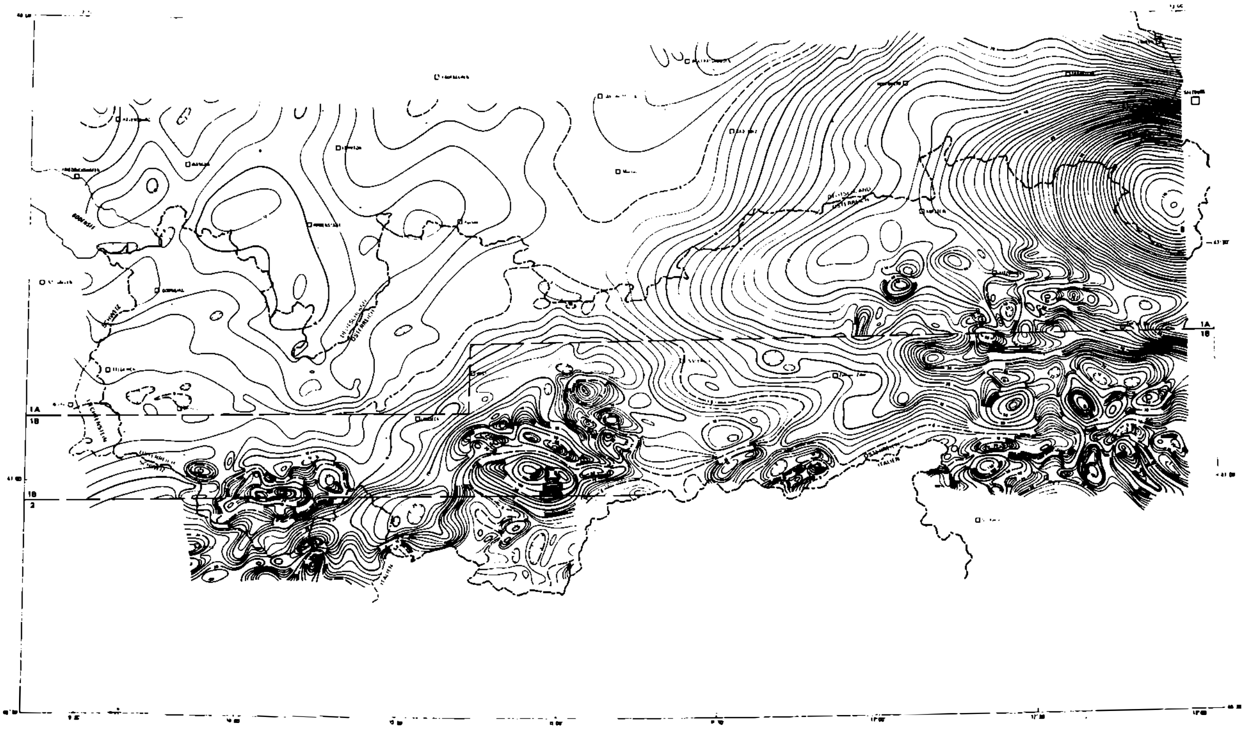

Fig. 5: Aeromagnetic Map of the western and central part of the Eastern Alps.

Some of these anomalies are already interpreted quantitatively by two- or three-dimensional model calculations. This was done mainly in view of the physical parameters and the dimensions of the involved bodies but neglecting questions of the real shape of these bodies. Thus it was possible to use only simple models as the sphere and the rectangular prism, even in cases where it is evident from surface geology that more complicated models would be necessary for a realistic approximation of the shape of the magnetic bodies.

In the case of the Ötztal-anomaly, which is caused by amphibolites, gravimetric measurements are available in addition. A positive Bouger-anomaly of approximately 10 mgal coincides with the aeromagnetic anomaly. Also gravimetric and magnetic model calculations are in good correspondence [53].

2.6 The Gravimetric Alpine Traverse (GAT). (Publications 66, 18)

The Geodetic Survey of Austria (Bundesamt für Eich- und Vermessungswesen) has established a basic network of gravity measurements in Austria which is oriented strictly towards the purpose of the national geodetic survey. Therefore the gravity stations are exclusively tied to bench marks of level lines. Since level lines are organized mainly for the needs of the population and the economy within the Alps, they are concentrated to the densely populated valleys. As a result of this, in the Alpine part of Austria between different levellines, areas of 2000 km² and evenmore are left without any gravity stations. Bouguer anomalies based upon these data represent only regional trends in greater areas and therefore have limited importance for geodynamical questions.

Therefore the GAT project was started for IGP. Within this traverse the gravity stations are distributed on a grid pattern thus giving areal coverage of the traverse. The traverse extends North-South with a width of one degree longitude between 13°20' E and 14°20' E from the southern to the northern border of Austria. Limited in the East by the line Loiblpass — Klagenfurt — Froiach — Rottenmanner Tauern — Sengsengebirge — Linz — Bad Leonfelden and in the West by the line Naßfeldpass — Sachsenburg — Hochalmspitz — Radstädter Tauern — Tennengebirge Hausruck — Passau,the traverse cuts through all important Alpine geological units. Beginning in the South with the Southern Alps, the Austroalpine layers, the Tauern Window, the Graywacke-zone, the Northern Calcareous Alps, the Flysch-zone and the Molasse it ends in the North at the Bohemian Massif. In addition several faults, fracture zones and other tectonic features are situated in this traverse: the Periadriatic Lineament and the faults of Mölltal. The Malta-Gegendtal and the Ennstal are other examples for these features.

Besides the gravimetric investigation in the surroundings of the Periadriatic Lineament which has been discussed already, approximately 1100 gravity stations have been measured in this traverse with a mean station density of one point per 10 km². In addition at 40 stations the vertical gradient of gravity has been determined as well. Thus it was possible to show the areal distribution of the gravimetric vertical gradient after applying topographic corrections. In consequence it was possible to calculate free air corrections with the real gradient instead of using the normal gradient.

Evaluation and interpretation of these gravimetric data has first been concentrated to an area between the Hochalmspitz in the WNW and the Nock mountains in the ESE. The area under investigation is oriented almost perpendicular to the strike of the Bouguer isolines and extends from the easternmost part of the Tauern window to the western part of the Upper Austroalpine Gurktal nappes. Two Bouguer maps have been drawn, one using the conventional free air correction and one applying the actual vertical gradient in the free air correction term [66]. The latter one agrees very well with surface geology. There is a Bouguer minimum between Gößgraben and Malta valley which corresponds to the updoming gneisses of the Gößgrabenkern being part of the Taueranticline. At the rim of the Tauern Window the Bouguer gravity increases. In the small region of the schist cover and Lower Austroalpine a fairly high horizontal gradient of approximately 2 mgal/km can be observed while most of the middle Austroalpine units are characterized by nearly flat gravity gradient. The Permo Mesozoic Middle Austroalpine unit is indicated by a gravity trough while afterwards the increase of Bouguer values continues within the Upper Austroalpine Gurktal-nappe. The ore bearing Triassic of the Innerkrems as well as the magnesite bearing crystalline at the northeastern Millstätter Alpe are marked by positive Bouguer anomalies.

The Bouguer map based upon the conventional algorithm of corrections is by far less interpretable in terms of surface geology. The use of the actual vertical gradient thus enables an isolation of the residual part of the Bouguer field which has to be explained by the uppermost layers of the crust.

The conventional Bouguer map containing information from all layers of the earth crust is dominated by the pronounced gravity contrast of the Tauern window and the Gurktal nappe which results in an intense horizontal gradient up to 5 mgal/km. Gravity troughs mark the faults of the Malta- and the Möllvalley. It is interesting to note that the continuation of the Malta fault to the southeast the Gegendtal fault — is gravimetrically not detectable, at least between Gmünd and Radenthein. On the other hand there is a gravimetric indication for the continuation of the Feldkirchen-Patergassen fault to the Northwest. It seems it is traceable as far as north of Radenthein. Quantitatively these data are interpreted by three-dimensional model calculations (Ruess, personal communication 1979).

2.7 Magnetotelluric sounding (Publication 1)

Magnetotelluric measurements have been started 1978 in the transition zone between the Eastern Alps and the Pannonian Basin in cooperation with the Hungarian Geodetical and Geophysical Research Institute, Sopron. The sounding localities were situated along the ALP 75 profile and allow a comparison of the electric and the seismic crystal parameters yielded from the magnetotelluric and refraction seismic measurements respectively. Two conductive zones have been detected in depths of 7 and 32 km which correspond fairly well with the low velocity layers observed at the ALP 75 profile [1].

2.8 Geothermic measurements (Publication 55)

The ZA and the Niedersächsisches Landesamt für Bodenforschung, Hannover, have carried out temperature measurements in Alpine lakes for the purpose of heat flow determination as a cooperative project. The measurements were successful in six shallow lakes situated in Tyrol (Wachsee, Hechtsee) and in Trentino. Together with 26 heat flow values which have been published previously it is possible to distinguish schematically four different zones in the Alps:

	mean heat flow
northern Alpine foreland:	78 mWm^{-2}
northern Alpine margin:	125 mWm^{-2}
main Alpine area:	65 mWm^{-2}
southern Alpine margin:	125 mWm^{-2}

Different possible interpretations have been tested by model calculations [55].

3. Investigations of local structures

Detailed investigations of local size have been performed because of two reasons. On one hand areas were selected according to special tectonic questions which are of main structural importance for the geodynamics of the Eastern Alps (e. g. faults). On the other hand such investigations were started to gain detailed information (e. g. velocity distribution) which form the necessary background for studies of regional size. Simultaneously such measurements revealed the efficiency and applicability of various geophysical methods for treating Alpine geodynamics.

Some results of general interest are reported here.

3.1 Local gravimetric investigations in the Hohe Tauern Großvenediger and Felbertauern (Publications 34, 33, 46)

The Tauern Window consists of granitic rock formations surrounded by schists. One of the basic petrographic questions is to determine the origin of the metamorphism which is evident in all rocks of the window. The usual explanation is that of a regional metamorphism caused by thick layers of overburden. The alternative hypothesis is that huge magmatic granite-bodies intruded the Tauern area at the end of cretaceous times thus causing thermal metamorphism. Since a considerable size of these young granitic bodies (tonalites) is the necessary requirement for the latter hypothesis, gravimetric measurements were performed for testing this hypothesis in cooperation with the TU Clausthal [34].

Three-dimensional model calculations reveal that these young rock bodies end at a depth of approximately 1,5 km below the sea-level [33].

It has to be emphasized that these models are very schematic ones intending only to indicate the magnitude of the different bodies. These results demonstrate that it makes sense to divide the „Venediger-Kern“ complex into two different rock units as well as they are in favour of a regional metamorphism of the Tauern Window because of the fairly small dimensions of the tonalites.

Similar gravimetric measurements have been performed in the Felbertauern area where it was possible to put gravity stations in three different levels: into two tunnels and on the surface. Model calculations at all three levels reveal that the Bouguer anomalies are caused by different bodies of gneisses, schists and amphibolites [46].

3.2 The basement of the Inn valley (Publication 17)

A cross-section of the Inn valley was investigated east of Innsbruck. Reflection- and refraction seismic methods as well as gravimetry were used for these measurements. The thickness of the Inn valley sediments is 340 m. Reflection seismic data show two horizons within the sediments which are interpreted as water tables. At the northern margin of the valley an intermediate wedge between sediments and basement has been detected which is up to 300 m thick (see fig. 6). This wedge could be the geophysical indication of a mylonite zone or fault marking the boundary between the Northern Calcareous Alps and the crystalline rock formations. Fig. 6 shows the gravimetric model of the cross sections. The corresponding seismic V_p velocities are 2000 m/s, 3000 m/s and 4900 m/s for the sediments, intermediate wedge and basement respectively.

For fitting the gravity model to the observed Bouguer-values an iterative algorithm has been developed. Based on the gravitational attraction of rectangular prisms the theoretical gravity anomalies of an initial model are calculated. The differences to the observed gravity values are used for proportional changes of the prism dimensions. Consecutively the gravity calculations is repeated and usually after four iterative repetitions there is sufficient coincidence of the gravitational anomalies of the model with the observed ones [17].

One consequence of this investigation is of importance for the entire Alps and has to be pointed out especially.

The Bouguer gravity data show a difference of approximately 10 mgal between stations in the middle of the valley and marginal ones. It has to be concluded that the results of gravity profiles extending purely through mountain valleys have to be considered with great reservation. Due to the fact, that the basement of many valleys consists of a fault and due to the often unknown thickness of young sediments in the bottom of a valley, measured gravity values may be systematically erroneous, i. e. to low. Therefore it was inferred that profile oriented gravity measurements will not be of great help and that an areal distribution of gravity stations has to be achieved for obtaining a realistic picture of the Alpine gravity field. This was consequently followed in all gravimetric investigations of the IMG, like the Periadriatic Lineament survey and the GAT-project.

3.3 The Diendorf-fault near Melk (Publication 45)

In the area where the Danube joins a variscian transform fault — the socalled „Diendorfer Störung" — near Melk detailed geophysical investigations have been applied to trace this fault underneath the flat lying gravel and river sediments of the Danube valley. Mainly refraction seismic and gravimetric measurements were performed in a dense network of profiles and gravity stations respectively and revealed the deeply intended surface of the crystalline basement. In evaluating the gravimetric data the regional field was determined by a least square third order polynomial fit. The residual field is presented in fig. 7. It shows that two faults meet each

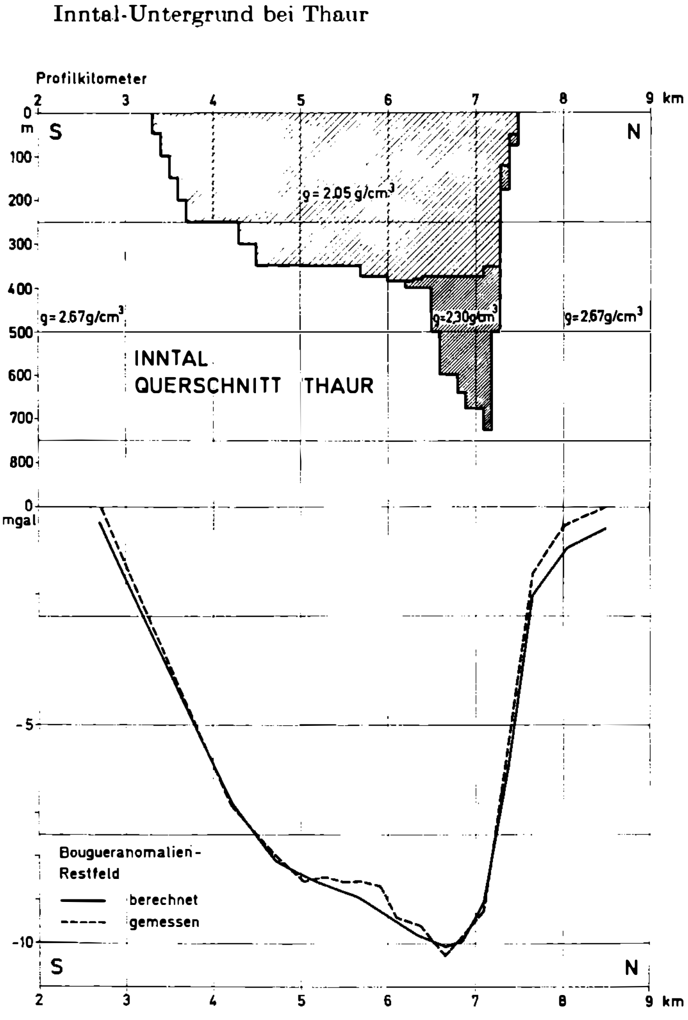

Fig. 6: Cross section of the two-dimensional gravimetric model of the Inn-valley basement [17]; top: model cross section; bottom: comparison of observed and calculated residual Bouguer anomalies.

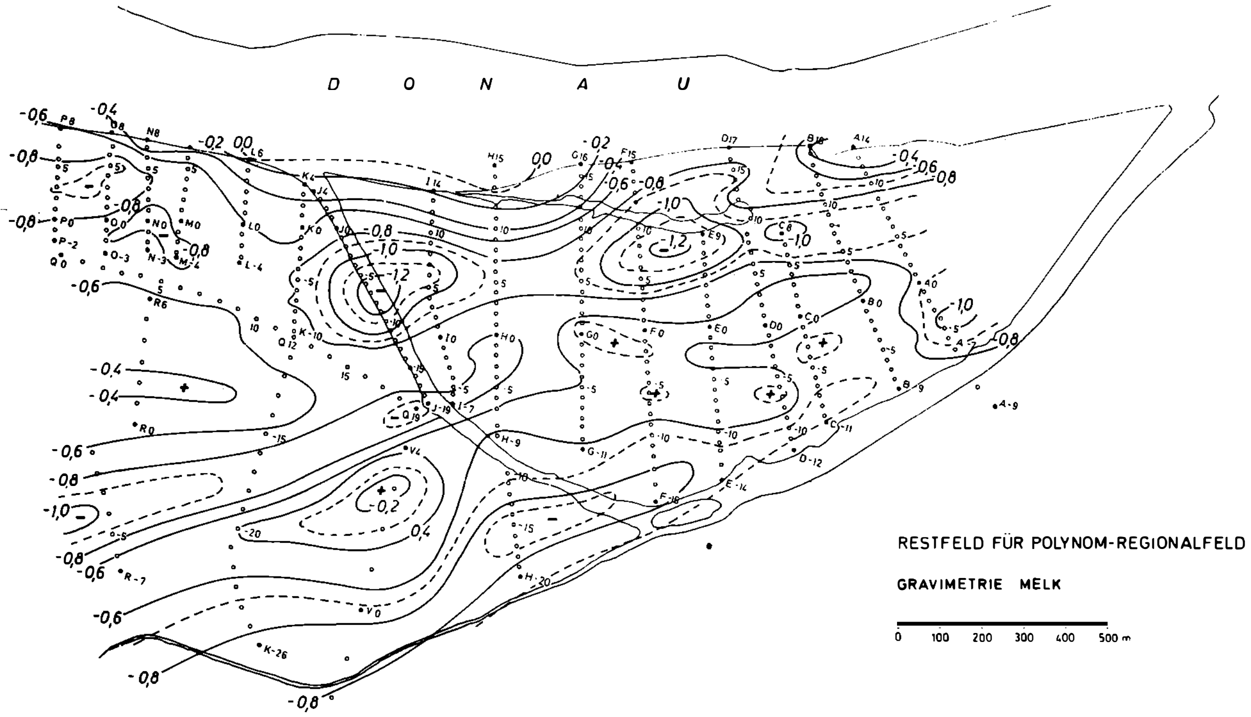

Fig. 7: Residual Bouguer anomalies of the fault system near Melk [45]. (Units in mgal.)

other in this area. One fault extends east-west just south of the Danube and is marked by a series of Bouguer minima. The second one is the Diendorf fault striking WSW-ENE which has a complicated structure consisting of two parallel troughs of Bouguer minima seperated by a ridge formed by a series of Bouguer maxima. Three-dimensional model calculations explain this as the deeply indented surface of the crystalline, where nearly vertical fault throws up to 80 m exist [45].

3.4 Seismic propagation velocities near the margin of the Tauern Window (Publication 2)

Refraction seismic measurements have been carried out in the easternmost part of the Tauern Window in the Malta valley and Gößgraben and outside the window at the Nöringsattel. The Penninic granitic gneisses of the Gößgraben show a velocity of $V_p = 4700$ m/s while the schists of the middle Austroalpine formation at the Nöringsattel have a V_p-velocity of 5500 m/s [2]. As the Penninic gneisses and schists are supposed to dip underneath the Austroalpine unit at the entire length of the Eastern Alps the resulting velocity inversion is of great importance for any refraction seismological investigation of the Alpine crust. Only advanced refraction seismic methods can untie such velocity distributions. Joint interpretation of refraction seismic data together with other geophysical results will improve the significance remarkably. In this case the GAT project, as it has been discussed already above, will serve for this purpose.

3.5 Interpretation of macroseismic data with regard to a velocity inversion (Publication 28)

A model seismic experiment has been carried out to explain the anomalous wide extension of the isanomals of East Alpine earthquakes to the north. This model consists of an outcropping low velocity-channel representing the Molasse layer over a half space with high P-velocity The latter represents the Bohemian Massif. The Nor thern Calcareous Alps lying on top of the Molasse layer are simulated in the model by a thin layer of high P-wave velocity. The model seismic experiments deduced that the low velocity channel acts as a wave guide if the seismic source is located close to that channel [28].

This explains the existence of a shadow zone for seismic energy in the Calcareous Alps and why in the northern foreland relatively greater earthquake intensities can be observed.

3.6 Seismic transmission function of the crustal structure in the Vienna area (Publication 64)

The fine structure of the earth's crust has been studied by means of far distant earthquake seismograms. The transmission function of the crust near Vienna using records of P-phases from long period seismographs at Wien-Kobenzl has been studied [64]. Calculations result in a thickness of the crust of **31 km**. The best approximations have been obtained by a 4-layer model, determined with a trial end error method. However, the results are very sensitive to the choice of the initial model for this procedure. Therefore it has to be concluded that optimum benefit can be derived from this method in areas where no other source of geophysical information is available than a seismographic station.

3.7 Marginal basin of the Bohemian Massif (Publication 67)

Seismic and gravimetric measurements have been carried out in the basin of Horn with the aim to localize the Bohemian crystalline basement below the sediments [67].

The survey in the center of the basin between the two villages of Wörtersdorf and Karnegg yielded a thickness of sediments of about 100 m. The P-velocity of the basement of 4400 m/s represents a typical value for weathered and tectonically stressed crystalline Phyllites.

4. Geophysical indications of geodynamic processes

Two different methods have been used to detect geodynamic processes which caused the orogenesis of the Alps. On one hand the isostatic behaviour of the Alpine system was compared with recent crustal vertical movements and on the other hand paleomagnetic investigations were started to study movements of different Alpine units as well as global geodynamic processes like plate tectonic movements and the mechanism of geomagnetic field reversals.

4.1 Recent crustal movements and isostasy in the Hohe Tauern (Publication 86)

Recent crustal movements have been observed in the area of the Hohe Tauern indicating an uplift of about 1 mm/year of the southern part of the Tauern Window in comparison to the Salzach valley. Uplift caused by isostasy requires a mass deficit in the uplifting crust. On the base of a crustal model of the approviate Alpine cross section it can be demonstrated, that the crustal uplift of the southern Tauern Window is not in accordance with an isostatic compensational movement. In fig. 8 on top the mass balance for this cross section is shown which indicates that the masses within a crustal column increase continously from north to south.

Below the mass balance the uplift rates are presented which are positively correlated to the mass balance curve (instead of having a strong negative correlation as it is demanded by isostasy). As mean topographic heights are considerably greater in the South than in the North it can be concluded that this process is continuing already since a longer period. The overall conclusion is that lateral forces acting from the South could be the cause for this uplift [86].

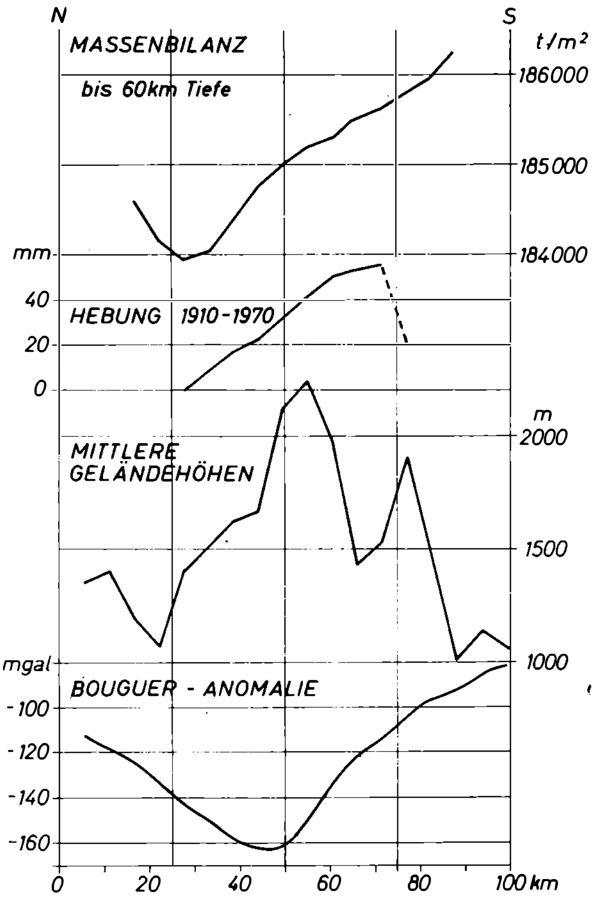

Fig. 8: Hohe Tauern cross section showing from top of bottom mass balance, uplift 1910—1970, mean topographic heights and Bouguer anomaly [86].

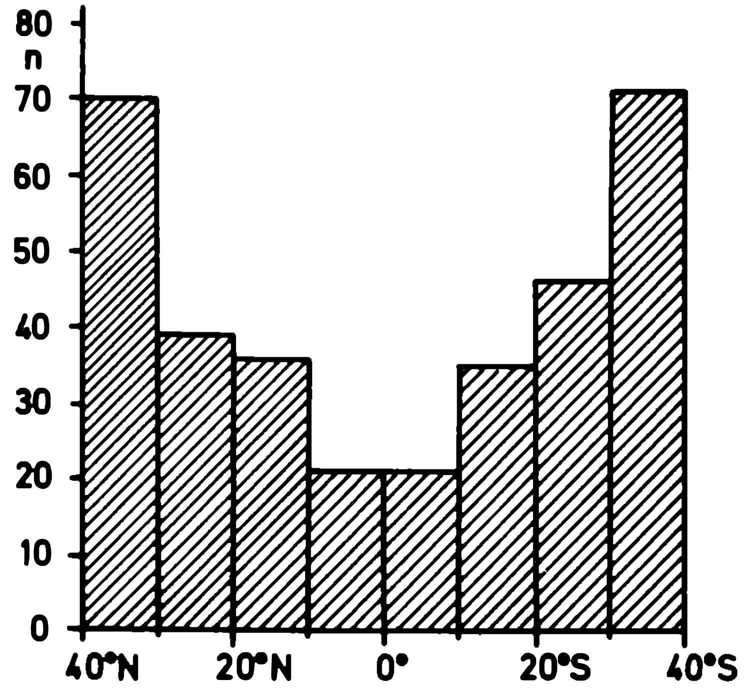

Fig. 9: Latitudinal frequency distribution of paleopoles during polarity transitions [88].

4.2 Behaviour of the geomagnetic field during polarity transitions (Publication 88)

Since paleomagnetic interpretation regarding tectonophysical questions is always conducted using the hypothesis that the geomagnetic field behaves dipolar and is oriented in average parallel to the earth's axis of rotation. As polarity reversals are a wellknown fact it is interesting to investigate the behaviour of the geomagnetic field during these transition periods when deviations from the above described hypothesis have to be expected.

Data of 23 field reversals of recent, Tertiary and Upper Mesozoic age containing approximately 350 paleopole positions between latitudes of 40° N and 40° S were examined in cooperation with St. Louis University. The result is a latitudinal frequency distribution of paleopoles of a U-shape type (Fig. 9). This can be interpreted as a flip over of the geomagnetic field which gains speed when its axis approaches the equator. Paleointensity studies reveal that the moment of the transitional field becomes progressively weaker when its axis advance towards the equator but retains still comparatively high values during the greater part (ca. 90%) of the transition time interval. Only for a very short period when its axis is within the latitudes of 10° N and 10° S the geomagnetic moment becomes very weak.

Quantitatively the following table summarizes the properties of geomagnetic transitional periods:

Latitudinal interval of paleopoles	40°—30°	30°—20°	20°—10°	10°—0°
Mean magnetic moment in arbitrary units (axial dipole field = 100)	60	45	27	10
Mean transitional velocity in arbitrary units	30	49	59	100
Average time of transition in percent	42	25	21	12

The results discussed so far are valid whether the geomagnetic field remains dipolar or become multipolar during the transition. Nevertheless, some statistical hints have been detected suggesting that at least in some cases the geomagnetic field keeps its dipolar character during the reversal [88].

4.3 Plate tectonics investigations by paleomagnetic methods (Publications 93, 94, 89)

The evolution of the Alps is a very complex one in terms of plate tectonics and can be seen in connection with differential movements of the faster African and the slower European Plate and the Mediterranean region in between which contains some microplates. It has to be expected that comparative studies in regions with a less complicated tectonic history might be helpful in solving geodynamic questions of the Alpine orogenesis. As region for this comparative investigation the Carribean was chosen. The Carribean is situated between the North American and the South American Plate with the latter one moving faster. It is, of course, evident that the comparability between Carribean and Mediterranean is a limited one. Anyway, some similarities in the tectonic situation between the Alps and the mountain ranges of the Greater Antilles situated at the northern margin of the Carribean are of interest. Therefore together with St. Louis University paleomagnetic investigations have been performed in Jamaica [93] and Hispaniola [94.]

The results can be interpreted in terms of plate tectonics and yield an anticlockwise rotational movement of the Carribean plate over a distance of approximately 1000 km to the Northeast since Lower Cretaceous [89]. relative to North America. Some Paleopoles in equatorial latitudes suggest additional local rotations of the islands as marginal blocks of the Carribean plate probably caused by the differential movement of the adjacent plates. Similar rotations have been observed in the Mediterranean as well.

4.4 Paleomagnetic studies in the Alps (Publications 82, 79)

Systematic paleomagnetic investigations in the Eastern Alps have to be directed to several problems. One basic question is to examine how far the curve of apparent polar wandering for stable Europe can be used as reference for the interpretation of paleomagnetic results from the Eastern Alps. This will enable the systematic paleomagnetic study of the different Alpine rock units, structural geological features and their geodynamic behavior. Especially the Northern Calcareous Alps and the Periadriatic Lineament are of great interest with regard to this objective. Also the importance of metamorphism for the rock magnetic properties has to be investigated. This requires cumbersone studies because the orientation of the original remanent magnetization will be changed not only by the metamorphic VRM but also by anisotropy effects caused by the high stressrates of the metamorphism process.

It was necessary to furnish the new paleomagnetic laboratory with instruments especially suitable for the research objectives described above. Sedimentary rocks, which are measured primarily, are usually characterized by an extremly weak magnetization. The Medium NRM of rock samples from the Northern Calcareous Alps is approximately in the range of 7.10^{-7} emu which is only a little bit more than the sensitivity of modern spinner magnetometers. Therefore only small possibilities are left for demagnetization experiments. A superconducting SQUID-magnetometer was installed, which allows the detection even of diamagnetic rock samples (e. g. occassionally observed in marbles) and enables the investigation of considerably lower magnetized rock samples with higher accuracy. Great care is also necessary for avoiding viscous remanent magnetization effects during measuring and demagnetization procedures of weakly magnetized samples. Therefore mumetal shields are used for all instruments and storage boxes for protection against the earth's field and its variations. Within the shielding typical values of the residual field are for instance ±1 nT in the oven of the thermal demagnetization apparatus. To avoid rotational remament magnetization effects (RRM) a shielded static alternating field demagnetization system was chosen instead of a thumber [82].

Paleomagnetic investigations of the basalts of the Pauliberg/Burgenland contribute to the polar wandering studies. Rock samples from this volcano of Upper Tertiary age have been treated with the usual paleomagnetic methods. The mean direction obtained after applying „cleaning" procedures are the declination $D = 10{,}0^{\circ}$ and inclination $I = 63{,}1^{\circ}$. This direction agrees very well with results from Styrian vulcanites indicating a Dacian age of the Pauliberg basalts. The paleopole position obtained from this direction fits to the European polar wander curve [79].

Within the Northern Calcareous Alps the situation of the „Weyrer Bögen" an arcuate structure of nappes has been investigated in cooperation with the Institut für Geologie of the University of Vienna. Conflicting hypotheses exist concerning the primordial orientation of the sedimentary basin. One suggests an arcuate shape of the basin while the other assumes sedimentation in a straight shaped basin and a later rotation of the nappes. Paleomagnetic studies can test these hypotheses by calculating angles of rotation for rock samples of appropriate sites within the „Weyrer Bögen" and outside the questionable area. Sites of comparable age and bedding yield the following preliminary data. (Site names describe only approximate location).

site location related to Weyrer Bögen		predicted angle of rotation	paleomagnetic determined angle of rotation
outside	inside		
Frankenfels	Brunnbach	86°	70°
Losenstein	Unterlaussa	97°	105°
Reichraminger Hintergebirge	Palfau	38°	45°

Correspondence between predicted and calculated rotations is good enough to support the rotational hypothesis of the origin of the Weyrer Bögen.

5. Recent tectonic processes and movements

Earthquake seismology is the principal tool for studying recent geodynamics of the Alps.

In addition recent crustal movement and earthtide measurements delivered information concerning recent geodynamics.

5.1 Earthquake studies

Seismic activity in Austria is from low to moderate. The yearly rate of 15—25 perceptible earthquakes is comperably small, and this reduces its statistical value as information source about plate tectonics. The fact that catastrophic earthquakes occured in Friuli 1976 has changed this somewhat as these earthquakes were accompanied by many fore- and aftershocks. This activity continues still today. Untill summer 1979 more than 3000 seismic events of Friuli have been recorded by Austrian seismographic stations. Fortunately from the beginning of IGP the seismological station network of Austria has been improved and expanded continuously by IMG and ZA. This was a necessary condition for a more distinct and accurate study of earthquake zones in Austria. Also the evaluation and geodynamic interpretation of macro- and microseismic data has been improved and extended.

5.1.1 Evaluation of macro- and microseismic data
(Publications 92, 24, 39, 40, 48, 57, 47, 26, 27, 68, 51, 35, 25, 23, 38, 41)

The earthquake catalogue of Austria has been revised and updated to gain full information on Austrian seismicity [92].

In the beginning of IGP the severe earthquake of April 1972 at Seebenstein gave evidence for the necessity of enhanced seismological activity in Austria. This earthquake has a maximum intensity of $7{,}75^{0}$ of the MS-scale and a fairly large magnitude of 5,4. Besides the epicentral region also heavy damages occurred in the northern part of Vienna in a distance of approximately 60 km north of the epicenter. This unusual pattern of damages can be explained by resonance effects of the uppermost Quarternary layer [24].

The macroseismic data of the great earthquake at Namlos 1933 collected by the Bavarian seismological service and the ZA was studied [39]. They used this data to prove a new method for determing the focal depth H and the extinction coefficient a of seismic waves. The same method has been applied to 72 East Alpine earthquakes [40]. It is shown that 72% of the hypocenters are situated in the upper crust. An increase of the extinction coefficient for deeper foci indicates a zone with low shear resistivity.

The geographical distribution of East Alpine earthquakes was investigated by using material of the ZA and from other sources [48]. The epicenters are correlated with the areas where great geological fault systems cross each other, i. e. the Mur- and the Lavantfaults.

The macroseismic data of the Friuli earthquake (May 1976) obtained by the ZA and other European institutions have been compiled by an international group resulting in a map [57].

The „relative intensity" represents a correction term δI applied to the expected intensity I observed at a location at a distance Δ to the epicenter of an earthquake with the maximum intensity I_0, the azimuth ϕ and the focal depth H [47]. The "relative intensity" can be estimated empirically. It depends on the local geological conditions in a complex manner.

The catastrophic Friuli earthquarkes of May and September 1976 affected also Austria. A short description of the three strongest earthquakes was given and macroseismic maps of all important aftershocks for the territory of Austria were presented [26]. In addition a historical summary as well as a selection of isoeismal maps of historic shocks are shown.

Macroseismic investigations of the severe earthquake of September 1978 in the western Swabian Alb revealed a better perceptibility of the earthquakes north of the Alpine main crest than south of it [27]. An improvement of the P_G- and S_G-traveltime curve of near earthquakes has been proposed for the seismographic station Vienna [68]. An empirical relation of the sensitivity of the station Vienna to earthquakes of different distances and magnitudes has been proved [51]. Empirical P_n- and S_n-traveltime curves for 3 different classes of focal depths are presented.

An international working group with participation of he IMG has determined focal parameters of 18 selected major aftershocks of Friuli, which occured between May 6 and September 15, 1976 [35]. Observations from many European seismic stations and also from mobile stations in the epicentral area were used for this purpose. For deriving more quantitative information from macroseismic observations the relation between maximum acceleration and the local intensity on the MSK-scale has been determined for Vienna [25].

A formula on the assessment of maximum earthquakes in the Alps and adjacent areas was developed [23]. This formula is based on the relation between fault length and magnitude M of an earthquake. This is possible because the magnitude is a function of the seismic energy which is proportional to the focal volume and consequently related to the focal length. Assuming that the entire fault length is involved in the earthquake process the maximum earthquake can be estimated, so far as $M < 7$ is valid.

Recurrence periods for strong earthquakes are investigated for Central Europe. Earthquakes with an epicentral intensity of at least 8° MS are followed by a fairly strong aftershock after an average period of 130 days. A second recurrence period of about 40 days seems to exist too [38].

5.1.2 Improvement and extension of the Austrian seismographic station network (Publications 58, 19)

In the beginning of the IGP the seismological service of the ZA operated 5 stations in Vienna, Wien-Kobenzl, Innsbruck, Molln and Kremsmünster with recording speeds of 30 or 120mm/min. For studying the East Alpine seismicity between the Carpathians and Friuli a higher time resolution of the recordings is as necessary as are additional stations located in the active seismic zones. At selected sites, where suitable conditions were indicated by noise level measurements, 6 new seismographic stations have been put into service, located in Pitten, Mariazell, Glashütten, Klagenfurt, Bleiberg and Malta. Fig. 10 shows the station network and the distribution of epicenters 1903 to 1973.

The stations are equipped with short-period seismographs (Geotech S 13). The total transmission characteristic of the system is tuned to a frequency range of 0.25—20 Hz. High time resolution is gained by a recording speed of 300 mm/min, which allows distinct seperation of different seismogram onsets.

The instruments of these stations have been standardized in their transmission characteristics [58].

5.1.3 Determination of focal coordinates and earthquake magnitudes (Publications 48, 49, 10, 29, 21, 36, 37, 30, 6, 20, 22)

The resolving power of this network with regard to focal coordinates has been studied [48], showing that the geographical distribution of the stations is best for the localization of earthquakes in the area of the Mur-Mürz fault system.

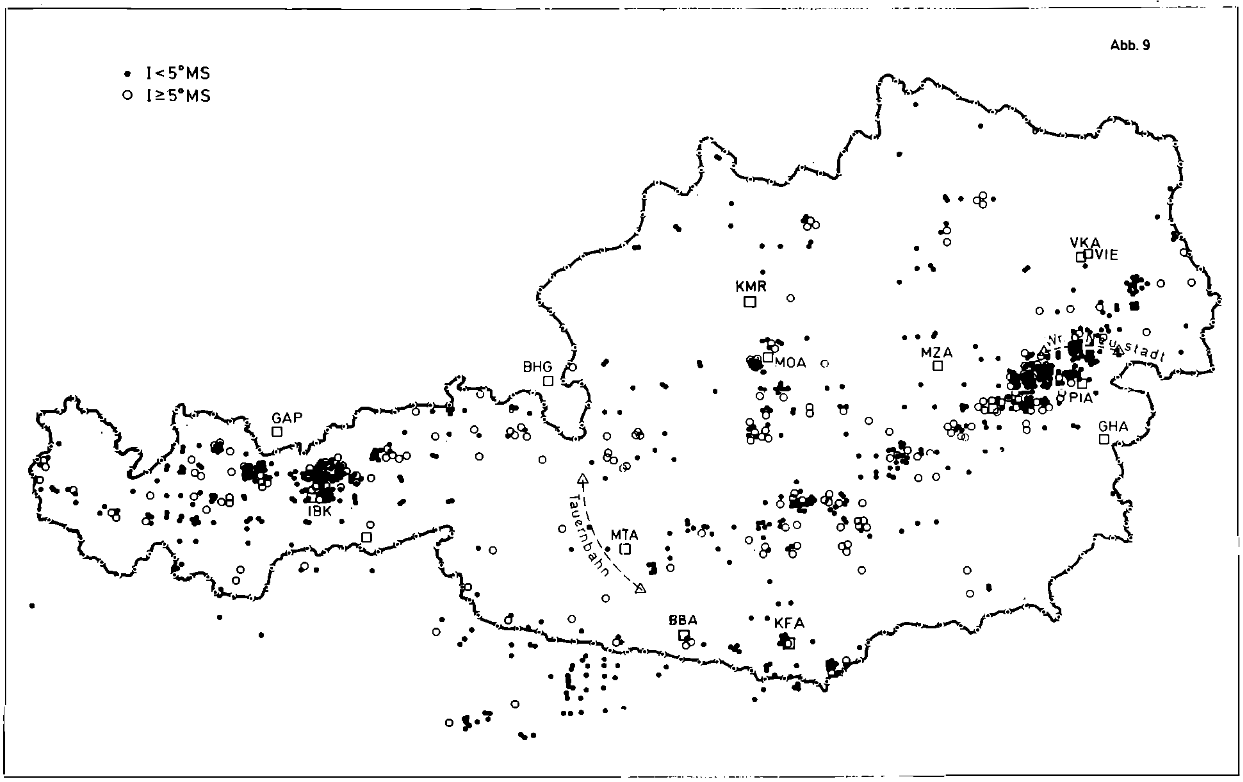

Fig. 10: Distribution of epicentres 1903—1973 and seismographic stations

VKA	Vienna-Kobenzl	BBA	Bleiberg
VIE	Vienna-Hohe Warte	MOA	Molln
PIA	Pitten	KMR	Kremsmünster
MZA	Mariazell	IBK	Innsbruck
GHA	Glashütten	GAP	Garmisch-Partenkirchen
KFA	Klagenfurt	BHG	Berchtesgaden
MTA	Malta		

A new computentional method using P_n- and P_G-arrval times of near earthquakes has been developed to determine focal coordinates, focal time, P_n- and P_G-velocity and the Moho-depth by a least square-fit of time errors [49]. With this method new hypocenter determinations of some earthquakes were performed showing that the foci in the Tauern are situated in the lower crust and those in the foreland of the Alps in the upper crust [10, 29].

Studies concerning the determination of earthquake magnitudes within a wide range of distances and periods have been carried out. One goal was to develop procedures for determining body wave and surface wave magnitudes by means of one seismograph with broad band recording characteristics [21].

The relation between the frequency and the magnitude of microshocks in the area of Molln is investigated [36]. It is shown, that the seismicity there is below the average of Austria. The great number of the Friuli aftershock enables a direct correlation between the signal duration, observed in Molln and the magnitude [37].

An empirical formula connecting the magnitude M, the amplitude A and the t_s-t_p-arrival time difference is developed. The knowledge of the epicentral distance is not necessary for using this formula. This advantage has been applied to another computational program for determining East Alpine epicenters. Observations of the dominant frequency of shear waves ($\triangle$ = 30 km to 500 km) indicate a clear dependence on the maximum intensity [30].

An empirical formula relating the magnitude, maximum intensity and focal depth h has been deduced from records of many Friuli aftershocks [6]. This formula is $\log h \text{ (km)} = 0{,}45\, M - 0{,}28\, I_0 + 0{,}80$.

The Leoganger Steinberge [20] and the neighboring Steinernes Meer area [22] were exposed to minor but unusual earthquake activity. Focal depths for these earthquakes were scattered around 10 km, thus indicating an origin within the crystalline basement, which has been overthrusted by the Northern Calcareous Alps. The magnitudes of these earthquakes, ranging from 1,6 to 3,5 have been estimated by an empirical formula based on macroseismic determinations of maximum intensity and focal depth:

$M = (2/3)\, I_0 + (8/3)\, \lg h - 2{,}57.$

Both formulas agree quite well, although they have been derived from earthquake observations in the Southern and the Eastern Alps respectively.

5.1.4 Fault plane solutions (Publications 44, 42, 14, 15, 29)

A comparative investigation of focal mechanisms of earthquakes in the Eastern Alps and the Dinarides reveals the dominance of horizontal motions of earthquakes and consequently their strike slip character within the investigated area. Further it is shown that the axis of maximum pressure is always oriented towards the Adriatic Sea [44].

GEORG GANGL

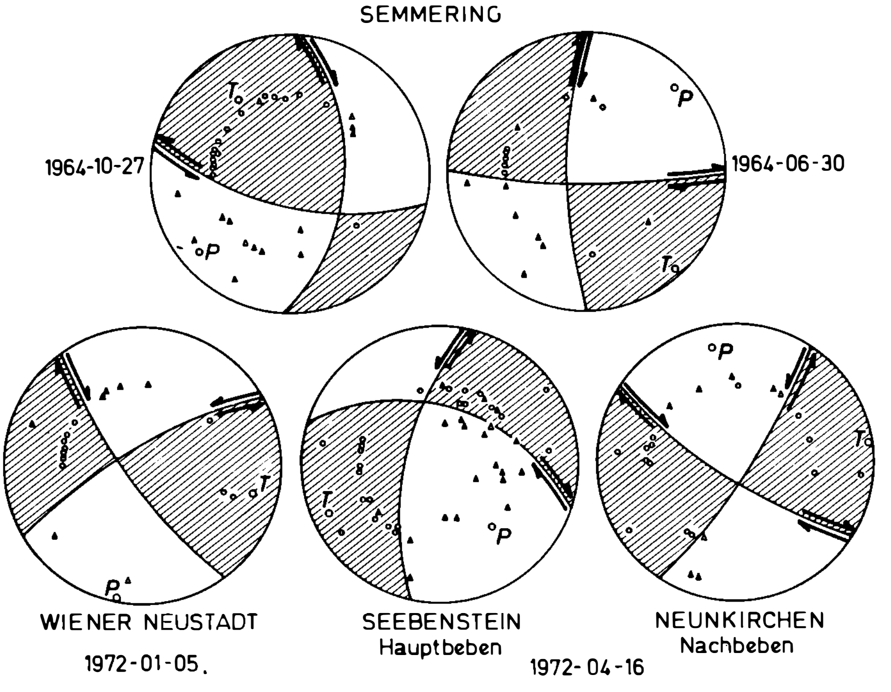

Fig. 11: Distribution of compression (circles) and dilatations (triangles) of the first motion of P-waves shown on the lower half of the focal sphere [42].

Within the Eastern Alps i. e. the eastern margin of the Alps the earthquakes belong to a NNE-SSW striking zone of increased seismic activity. The earthquake foci are situated in the upper crust (average depth: 9,9 km). The fault plane solutions obtained from the direction of first arrivals show predominantly horizontal motion.

Fig. 11 presents fault plane solutions for five typical earthquakes. Both Semmering earthquakes of fig. 11 are characterized by stress relaxation perpendicular to the strike of the Alps. The other three investigated earthquakes show focal mechanisms with maximum compression in N-S direction and maximum tension in E-W direction [42].

Twelve of 14 greater earthquakes in the area east of Judenburg indicate a tensional stress field oriented perpendicular to the alpine strike, i. e. more in E-W direction [14]. Probably this area is influenced by the forces initiated by the subsiding Pannonian Basin. According to this assumption the Viennese Basin, the Semmering and the eastern part of the Mur-Mürz Valley can be interpreted as a marginal fault system of the subsiding Pannonian block [15]. This conclusion fits into the concept of mantle diapirs below of the Pannonian Basin.

The earthquake of Molln (1967-01-29) has been investigated in detail [29]. This earthquake has a dipslip (compressional) fault plane solution with the B-axis oriented N 68°E. As far as macroseismic observations are concerned similarities with the earthquakes of Scheibbs (1876) and Neulengbach (1873) are evident.

5.1.5 Seismicity studies in Carinthia (Publications 8, 5, 12, 31, 7, 9, 13)

The series of Friuli aftershocks 1977—1978 indicate a correlation with the local seismicity in the lead mine of Bleiberg sofar only the mean activity in time intervals greater than 30 days is regarded. Single aftershocks of Friuli do not correlate with single local shocks in the mine [8]. Very small shocks occurring in the mine or nearby can be partially interpreted as man-made earthquakes (mine bumps), since blasts have been excluded.

The correlation of various earthquake events recorded at the seismographic station Bleiberg with the radon content of the nearby hot spring in Villach has been investigated. Corrections for changes of ground-water level, atmospheric pressure and precipitation have been applied [5]. This investigation has the goal to seperate tectonically and meteorologically induced changes of radon content, as this could be the basis for a tentative physical earthquake prediction.

Traveltimes of seismic waves from Friuli earthquakes recorded at Austrian seismographic stations have been used to construct a P-wave velocity model of the crust. Improvements concerning lateral veriations are still necessary [12].

The focal volumes of the main shocks of Friuli have been deduced from the area of aftershock activity which surrounds the main foci. The results agree well with those of other authors [31]. Using the t_s-t_p records of Bleiberg (Austria) and Trieste a value of $V = 10^4$ km^3 was determined for the main earthquake of May 6, 1976.

5.2 Recent crustal movements and earthquakes (Publications 42, 84)

Repeated precision levelling surveys of various level lines performed by the Bundesamt für Eich- und Vermessungswesen (Geodetic Survey of Austria) provide data concerning recent vertical movements in Austria. Some of these movements seem to be in connection with earthquakes.

After the earthquakes of Wr. Neustadt 1972 and Seebenstein 1972 repetition levelling of two lines (measured previously 1956—1961) indicated subsidence of the Wr. Neustadt basin. Maximum subsidence of 16 mm has been measured close the village Neudörfl east of Wr. Neustadt. This agrees very well with the fault plane solutions of the above mentioned earthquakes (see fig. 11), indicating tensile stress in this direction [42].

The level line Villach-Thörl Maglern has been measured in 1952 and 1964. After the Friuli earthquakes 1976 an additional survey of this line was performed in October 1976. From 1952 to 1964 a southward oriented uplift of 12 mm occured, while from 1964 to 1976 a downward movement of 4 mm was observed. This change of direction of recent crustal movements can be explained by the rebound mechanism of the Friuli earthquakes.

These earthquakes have a focal mechanism of the underthrusting type. For those earthquakes the rebound mechanism predicts in medium distances to the epicenter a preseismic uplift of the underthrusted block and subsidence due to the seismic rebound. As the geodetic observations are consistent with the mode described here, the recent movements may be interpreted as rebound effect of the Friuli earthquakes [84].

5.3 Earth tide investigations (Publications 61, 32, 60)

The La Coste & Romberg microgal gravimeter D-9 has been used for earth tide recordings. Three stations on a profile extending from the center of the Eastern Alps to the Pannonian Basin have been measured so far, namely Innsbruck, Vienna and Tihany (Lake Balaton). The purpose of this investigation is to determine whether the changing crustal structure between Alps and Pannonian Basin is of importance for the tidal parameters. In addition the deformation coefficient for tidal corrections of gravity measurements in this area has to be evaluated and information concerning the non-elastic behavior of the crust shall be gained.

At each station recordings have been performed for time intervals of more than 70 days. The analysis of records is performed by standard procedures of T. Chojnicki and ICET respectively which are in worldwide use [61].

As example for the analysis according to Chojniki observations at Vienna — Hohe Warte are presented.

Recording period: 71 days	group symbol	amplitude factor
	S_2K_2	1,180 ± 0,004
	M_2	1,184 ± 0,002
	$K_1P_1S_1$	1,154 ± 0,003
	O_1	1,171 ± 0,004

Comparisons with Tihany observations indicate systematic differences

group symbol	ratio of amplitude factors Vienna/Tihany
S_2K_2	99,5%
M_2	99,7%
K_1	101,2%
O_1	100,1%

(Meurers, personal communication, 1979).

Further the hypothesis is tested, whether the horizontal component of the earth tides can trigger earthquakes. Approximately 450 Austrian and Friulian earthquakes of the period 1900—1977 have been used for a statistical investigation. For the time of origin of each earthquake the azimuth of the tidal vector has been calculated. For these azimuth angles the frequency distribution shows two maxima in a distance of approximately 90°. In different earthquake zone of Austria the orientation of fault zones coincides with the maxima of the distribution. This correlation of fault orientation and earth tide azimuth points to a triggering effect, which is of interest for questions of earthquake prediction [32].

6. Contributions to potential field investigations

Potential methods have been applied to gravimetric and geomagnetic data as well as theoretical and methodological questions connected with geodynamic research objectives have been treated during IGP.

6.1 Geomagnetic field transformations (Publication 73)

Various transformations of the total intensity data (T) of the earth's magnetic field have been investigated. The reduction to the pole, which is a very important transformation, was applied to the T-residuals of the Eastern Alps. Because of this, almost all T-anomalies with a strike direction W-E are shifted to the North by approximately 15—20 km and are now situated just above the disturbing bodies. Also the transformation of the anomalous T-vector into its components (x, y, z) have been used for transforming the T-residuals of the Eastern Alps into Z-residuals [73].

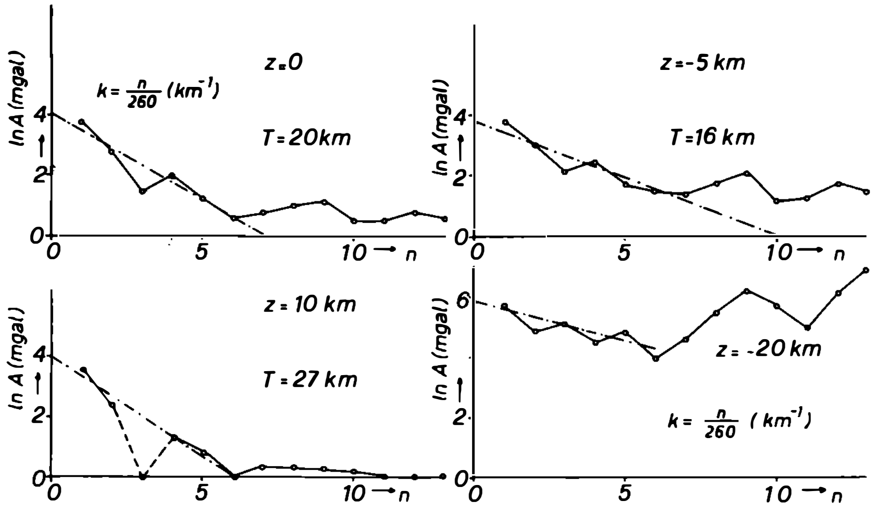

Fig. 12: Depth estimation of the gravimetric source by means of harmonic analysis for a N-S profile in the Hohe Tauern [73].

6.2 Gravity field investigations (Publications 73, 74, 66, 83, 85)

Upward and downward continuations of the gravity field of the Eastern Alps have been calculated as well. The field was projected upward to the elevations 10, 30 and 100 km and downward to —5 km. A depth estimation of the gravimetric source has been performed by means of harmonic analysis for the conspicious Bouguer gravity minimum of the Hohe Tauern area. Fig. 12 shows the amplitude spectra of a N-S profile for projection elevations 0, 10, —5 and —20 km and the depth estimation T from the projection height to the theoretical layer of origin. This depth estimation — giving a maximum depth — is derived from the slope low frequency Fourier amplitudes, which becomes zero if the layer of origin itself is chosen as projection height.

According to fig. 12 the causing body of the Bouguer minimum of the Hohe Tauern is situated in the upper crust in a maximum depth of 17 to 21 km [73].

A comparison of the power of the two-dimensional harmonic analysis and the convolution method in potential field transformation has been performed. Harmonic analysis yields slightly better results for greater continuation heights, while the influence of the periphery of the measuring plane to the frequency response of the actual field data has to be considered as a minor shortcoming of this method [74].

As it is not possible to determine the vertical gradient of the gravity field directly, experimental and mathematical approaches have been tested in the area of the GAT-project. Experimental determinations were performed by measuring gravity differences at two positions one upon another. The upper position is measured on a tripod, which causes some problems concerning stability. The LaCoste & Romberg microgal-gravimeter D-9 has sufficient sensitivity to reduce the height dimension of the tripod to approximately 1,6 m. This enhances the accuracy of the measurement considerabely. In addition the vertical gradient was computed for the same area with Bhattacharyya's formula out of the Bouguer anomalies. The comparison was carried out for 22 stations and resulted in a significant correlation. The correlation coefficient $r = 0{,}73$ is acceptable at the 99,9% level [66].

For performing such high precision measurements the calibration of the gravimeter has to be done very carefully and nonlinearities of the calibration factor have to be considered [83].

Additional problems arise from the high vibrational noise level of the European Calibration Line and minor inaccuracies in the gravity datum of the European Calibration Line. The latter one is caused by measuring errors as well as by the change from the International Gravity Formula 1930 to the Geodetic Reference System 1967 [85].

However, absolute gravity determinations in Austria should overcome these difficulties in the near future.

6.3 Relation between gravitational and magnetic field (Publications 72, 79, 75)

Because of Poisson's theorem there exists a simple relationship between the gradient of gravity potential and the geomagnetic potential. This relationship can be of great help for interpretation especially if ultrabasites have to be discriminated from other types of rock.

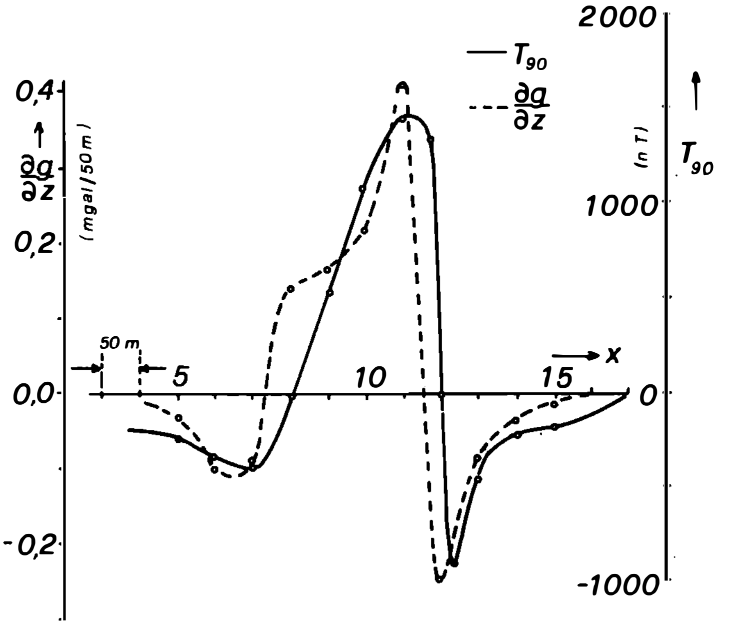

Fig. 13: Comparison of the total magnetic intensity values transformed to the pele (T_{90}) and of the vertikal gradient of gravity ($\delta g/\delta z$) at the Pauliberg [73].

This relationship has been applied to the gravimetric and magnetic data measured at the basalt outcrop of the Pauliberg near Landsee, Burgenland. It has been shown already that these basalts are part of the young volcanic activity of the Alpine orogenesis. They consist mainly of alkaline olivine basalts. Magnetic ($\triangle$T), rock magnetic and gravimetric measurements ($\triangle$g) were carried out over the Pauliberg in 1976. From two-dimensional model calculations the maximum thickness of approximately 60 m was deduced for the basalts [72].

After the transforming the $\triangle$T-values to the pole and calculating the vertical gradient of $\triangle$g (see fig. 13) Poisson's theorem was used in an attempt to obtain quantitative data on the density contrast of the Pauliberg basalts to the basement: calculated and measured density values are coincident [79].

Poisson's theorem has also been applied on a regional scale. There is some visual evidence of a correlation between the Bouguer anomaly δg and the residual δZ of the earth's magnetic field in the Eastern Alpine area. If this correlation is real, it should be caused by the same structure in the crust of the earth. To examine this, the gravimetric and magnetic data of parts of Central Europe were interpolated on a square grid with a grid spacing of $\triangle s = 10$ km. In the next stage the two horizontal gradients and the vertical gradient were estimated by means of approximation formulas. The correlation between these gradients and δZ was performed by evaluating the multiple correlation coefficient. Only in the eastern part of Austria a good correlation was found. To explain this result a test profile has been evaluated. Two-dimensional model calculations along a N-S profile in Central Austria indicate that the δZ-anomaly is caused by the upper boundary of the weakly magnetized crystalline basement. This has also a positive density contrast to neighboring formations, and contributions therefore to the Bouguer anomaly. But the total amount of the Bouguer anomaly contains also the effects of rock formations situated in greater depths, thus having temperatures well above the Curie point. Therefore these formations cannot contribute to the geomagnetic isanomalies [75].

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Appendix

Geographical coordinates of localities

Locality	Longitude East	Latitude North
Bad Deutsch Altenburg	16° 55'	48° 08'
Bad Leonfelden	14° 18'	48° 31'
Bleiburg	14° 48'	46° 35'
Brunnbach	14° 31'	47° 50'
Eberndorf	14° 39'	46° 35'
Fluela Paß	9° 57'	46° 46'
Frojach	14° 19'	47° 08'
Gmünd (Kärnten)	13° 33'	46° 55'
Gnesau	13° 58'	46° 55'
Gurk	14° 18'	46° 53'
Hechtsee	12° 10'	47° 37'
Hochalmspitz	13° 19'	47° 01'
Hochfilzen	12° 34'	47° 26'
Horn	15° 40'	48° 40'
Innsbruck	11° 24'	47° 16'
Judenburg	14° 40'	47° 10'
Klagenfurt	14° 19'	46° 37'
Köttmannsdorf	14° 14'	46° 34'
Körmend	17° 01'	47° 07'
Lavantsee (Judenburg)	14° 34'	47° 04'
Leoben	15° 06'	47° 23'
Linz	14° 17'	48° 03'
Loibl Paß	14° 16'	46° 26'
Losenstein	14° 26'	47° 56'
Matrei	12° 32'	47° 00'
Melk	15° 20'	48° 14'
Mont Revard	5° 59'	45° 40'
Naßfeld Paß	13° 17'	46° 33,5'
Nöring Sattel	13° 38'	46° 51'
Nufenen Paß	8° 23'	46° 29'
Obersee (Staller Sattel)	12° 12'	46° 54'
Orgiano	11° 57'	45° 21'
Palfau	14° 48'	47° 43'
Passau	13° 28'	48° 34'
Plöschenberg	14° 14'	46° 34'
Pyramidenkogel	14° 09'	46° 37'
Radenthein	13° 43'	46° 48'
Sabalahöhe	14° 10'	46° 34'
Sachsenburg	13° 21'	46° 50'
Sebenstein	16° 09'	47° 42'
Semmering	15° 50'	47° 38'
Stolzalpe	14° 11'	47° 07'
Unterlaussa	14° 27'	47° 57'
Unzmarkt	14° 25'	47° 12'
Villach	13° 51'	46° 37'
Völkermarkt	14° 38'	46° 40'
Walchsee	12° 20'	47° 39'
Wattener Lizum	11° 41'	47° 10'
Wiener Neustadt	16° 15'	47° 49'