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Structures and movements of the rock masses under the Eastern Alps

By GUSTAV ANGENHEISTER[1])

ABSTRACT

Between 1968 and 1978 gravity measurements, refraction seismic, geomagnetic and magnetotelluric studies were carried out in the Eastern Alps, especially along the Geotraverse *IA*. A brief account is given in this paper of some of the results of these researches concerning the physical properties of the rocks in the region, the anomalies of the earth's magnetic field, the structures near the surface in the vicinity of the "Alpen-Nordrand", the crustal structures under the Eastern Alps, the structure under the Moho and a kinematic model of the Northern Calcareous Alps. A technique is described for the calculation of the solid state convection in the material under the Eastern Alps.

ZUSAMMENFASSUNG

In den Jahren 1968 bis 1978 wurden in den Ostalpen, insbesondere auf der Geotraverse *IA* durch die Ostalpen (1968-1975), mit Methoden der Gravimetrie, Geomagnetik, Refraktions-Seismik und Magnetotellurik einige Strukturen a) des Deckenstapels, b) der mittleren und unteren Kruste und c) des oberen Mantels untersucht. Es wird hier nur über einen Teil der Ergebnisse berichtet. - Zu a): Die regionale Anomalie des Erdmagnetfeldes im Areal um Berchtesgaden wurde erneut vermessen. Die Anomalie ist relativ «glatt». Sie hat Halbwertsbreiten über 20 km, und es fehlt ihr ein N-Minimum. Verschiedene Interpretationen wurden diskutiert. Mit der Refraktions-Seismik und der Magnetotellurik wurde gezeigt, dass im Areal der Geotraverse *IA* unter dem nördlichen Teil der nördlichen Kalkalpen eine bis zu 4 km dicke Schicht wenig konsolidierter Sedimente liegt (vermutlich Flysch und Molasse). Hier war die Absenkung der Basis des Molassetroges maximal (über 8 km). Hieraus und mit anderen Kenntnissen folgt ein kinematisches Modell für die letzte Phase des Transportes der nördlichen Kalkalpen nach Norden. - Zu b): Längs des *A*lpen-*L*ängs*p*rofils (Refraktions-Seismik von Frankreich bis Ungarn, *ALP* 1975) konnte die Tiefe der Moho unter den zentralen Ostalpen bestimmt werden. Die mittlere Tiefe der Moho unter dem zentralen Teil der Ostalpen ist etwa 50 km. Im Übergang zur ungarischen Tiefebene nimmt die Tiefe der Moho auf einer Strecke von nur wenig über 100 km um etwa 25 km ab. Es wurden zwei Nieder-Geschwindigkeitszonen unter dem Tauern-Fenster gefunden. - Zu c): Unter den zentralen Ostalpen ist im oberen Mantel (unter der Moho) die Geschwindigkeit v_p der Longitudinal-Welle relativ hoch, was nicht nur aus der Refraktions-Seismik (*ALP* 1975), sondern auch aus der Untersuchung der Laufzeit-Residuen (beobachtet an zwei seismischen Stationen) folgt.

Dies Ergebnis spricht für relativ kaltes Material im oberen Mantel unter den zentralen Ostalpen. Ob es sich um Relikte einer Subduktion oder um eine heute noch existierende Subduktion handelt, kann mit dem hier diskutierten Beobachtungsmaterial nicht entschieden werden. (Da bisher unter den Ostalpen Tiefenbeben nicht beobachtet wurden, wird meist angenommen, dass gegenwärtig eine Subduktion unter den Ostalpen nicht existiert.)

Die Berechnung von Modellen der Unterströmung (Festkörper-Konvektion) wird skizziert. Um die Vorstellung von der Orogenese zu vertiefen, wurden im letzten Jahr Modelle von Strömungen unter den Ostalpen berechnet. Die Modelle hatten teils lokale und teils regionale Ausdehnung.

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Introduction

Between 1968 and 1975 gravity measurements, refraction seismic, geomagnetic and magnetotelluric studies were carried out along the Geotraverse IA through the Eastern Alps from Chiemsee to Venice. Some modern results of these researches, complemented in places by the results of geothermal and reflection seismic measurements in the vicinity of the profile, are described here. The Geotraverse IA was about 50 km wide, although this cannot of course be defined exactly.

Physical properties of rocks (along the Geotraverse IA)

The interpretation of measurements intended to give information about the deeper layers of the earth is improved when we know the properties of the rocks at or close to the earth's surface. The velocity v_p of *P*-waves (body waves with longitudinal vibration of the particles of the material) of various types of rocks have been measured in situ by hammer seismology, and on small samples in the laboratory by ultrasonic methods. v_p is extremely high in most rocks of the Northern Calcareous Alps. STÄDTLER (1973) and MARTINEZ (1976) found values in places even greater than 6 km/s. This agrees with the results of the refraction seismology, that v_p is about 5 km/s near the surface and increases up to 7 km/s at the base of the Calcareous Alps a few kilometers below the surface. - In contrast, v_p is less than 4 km/s in the Molasse rocks at the surface north of the northern boundary of the Alps ("Alpen-Nordrand"). A similar distribution of the electric resistivity ρ at the surface was found by the four point deep sounding method: The rocks of the Northern Calcareous Alps have high specific resistivity ρ (500 to 2000 Ωm at a depth of 100 to 200 m), and the resistivity ρ of the Molasse rocks is small (5 to 20 Ωm at 100 to 200 m depth). - Both v_p and ρ show clearly the differences between the older, permotriassic, partically chemically sedimented rocks and the younger, tertiary, lightly consolidated or unconsolidated rocks. (The Molasse sediments are young deposits carried from the mountains.)

The average magnetization of the rocks of the Northern Calcareous Alps is small. The magnetization of the rocks of the Tauern-Fenster (near the surface) is similar, both in intensity and variability to that usually found in rocks from the crystalline basement.

Anomalies of the earth's magnetic field

A number of local, and one regional anomaly, were found in the area of the Geotraverse IA. There is a much discussed positive regional anomaly ($\Delta T_{\max} \approx 120\ \gamma$, where T is the total field intensity) in the area of Berchtesgaden. This anomaly has been known for some time and has been measured often (A. Schleder and M. Toperczer 1936, R. Gaenger 1954, TOPERCZER 1968, U. Bleil 1974, BLEIL & POHL 1976). The last measurement of this anomaly was made during the aeromagnetic survey in 1978. The results of this survey, which covered only the Austrian section of the anomaly, have not yet been published.

Although it is not clear what role, if any, the source of this anomaly played in the dynamics and kinematics of the Alpine orogeny, it must be discussed here because of its great extent. There are three particular features of this anomaly: 1. Its horizontal extent is relatively large. The contours of the anomaly are approximately ellipses with major axes running WNW to ESE. The width between the half-intensity contours (half-width) is more than 60 km in this direction and about 30 km in the SSE to NNW direction. 2. The anomaly is remarkably smooth, that is: when some highly localized variations which certainly do not originate in the same magnetized body, are removed, the field variations are small compared with the maximum ΔT. It is more likely that such an anomaly is produced by a deep-lying body than by a very homogeneously magnetized body near the surface. Therefore the source of the anomaly probably lies deep, and because of the great width and uniformity of the anomaly it is possible that the top of the magnetized body is about 5 to 10 km below the surface. To give an intensity of about 120 γ at the surface a body at this depth must have a magnetization higher than that of most sediments. The field of a plate-shaped magnetized body, which could lie under the sedimentary cover of the Northern Calcareous Alps or could be part of the nappes system would fit the form of the anomaly. 3. Instead of the north minimum which many anomalies of the earth's magnetic field at our latitude have, there is a minimum to the south of the anomaly.

In general one of the following two possibilities are considered when interpreting anomalies of the earth's magnetic field. a) The remanent magnetization J_r is negligibly small compared with induced magnetization J_i or b) J_r is not negligible compared with J_i. Assuming a) the model body stretches northwards beyond the northern boundary of the Alps, the product of thickness times magnetization decreasing northwards. If the body is homogeneously magnetized the vertical cross section of the plate must be a very sharply pointed wedge. It must be pointed out that the real body could be formed from a number of not too widely separated pieces, which, situated at a depth of 5 to 10 km, would produce no distinguishable surface anomalies. When one looks at case b) it is possible by choosing the strength and direction of the remanent magnetization, to reduce the north minimum to zero and to produce a minimum to the south instead. In this case the resulting magnetization $\vec{J} = \vec{J_r} + \vec{J_i}$ is no longer in the direction of the earth's field at the location of the magnetized body, and the body does not have to extend so far north as it would if it carried no remanent magnetization.

If the magnetized body really does lie deep and is plate-shaped, and assuming that the magnetization is not extremely large, then it must be some kilometers thick, over 20 km long and over 30 km wide. In the very unlikely case that the body is a magnetite or pyrrhotite ore deposit it would have nearly the same horizontal extent and an average thickness of some hundreds of meters.

"Alpen-Nordrand" in the area of the Geotraverse I*A*

Seismic refraction profiles, with a length of some tens of kilometers, and magnetotelluric profiles with spacing of some kilometers were measured across the "Alpen-Nordrand" in the vicinity of the Geotraverse I*A*. The seismic refraction measurements (WILL 1975, 1976) and magnetotelluric measurements (KEMMERLE 1977, BERKTOLD et al. 1976) showed that slightly consolidated or unconsolidated sediments lie under the Northern Calcareous Alps south of the line between the Chiemsee and Rosenheim. The P-wave velocity and the specific electrical resistivity are much lower in these rocks than in the nearly 3 km thick covering layer of the Calcareous Alps. The seismic measurements indicate that the lightly consolidated layer is in places more than 3 km thick and that it ends about 20 km south of Rohrdorf (a shot point at the "Alpen-Nordrand"). It is not possible to say if the unconsolidated rocks with low P-wave velocity continue further south in a thin layer under the Calcareous Alps. - Under the "Alpen-Vorland" and under the Calcareous Alps the layer of high electrical conductivity (low resistivity) is thicker than the layer of low P-wave velocity, suggesting that perhaps deeper laying sedimentary rocks contribute to the integrated conductivity. This layer of good conducting, lightly consolidated rocks also appears to end about 10 to 15 km south of the "Alpen-Nordrand". Again it is not possible to say from magnetotelluric measurements if the good conducting rocks continue further south in a thin layer under the Calcareous Alps. The high conductivity (low resistivity) is possibly due to a high electrolyte content, implying that the material has a large pore volume. - It can be assumed that this lightly or unconsolidated layer belongs to the Flysch and or Molasse rocks units, which cannot be distinguished by the above methods. - Nothing will be said here about the economic significance of these structures, but their meaning for the kinematics of the Alpine orogeny will be discussed later.

A combination of seismic-refraction and magnetotelluric (and perhaps gravimetric) measurements has shown itself to be a very effective method of prospecting in the vicinity of the "Alpen-Nordrand". All three methods must, however, be specifically adopted to study the structure in that region.

Deep crustal structures under the Eastern Alps

Various seismic measurements have provided information about the structure of the crust under the Eastern Alps. These measurements include refraction profiles perpendicular and parallel to the axis of the Alps, reflection seismic studies in the "Alpen-Vorland" and earthquake observations (LIEBSCHER 1964, DOHR 1968, GIESE 1968, KOSCHYK 1969, Alpine Explosion Seismology Group, reporter H. Miller 1977; MILLER et al. 1977; H. Miller, personal communication 1979).

An important result of these studies has been to provide us with knowledge of the depth variation of the Moho. Here the Moho is defined as that depth interval in which v_p is about 8 km/s. Just above the Moho the vertical velocity gradient dv_p/dz is strongly positive, while just below the Moho dv_p/dz is only slightly positive. This definition says nothing about the thermodynamic and petrographic nature of the Moho.

Below the northern part of the Molasse trough the Moho is less than 30 km deep. South of the latitude of München the depth increases and is more than 35 km at the "Alpen-Nordrand". The depth increases further toward the south, and between the "Hauptkamm" (central main ridge) and the Periadriatic Line the depth is about 50 km. Under the Southern Alps the depth decreases again, to about 35 km at the southern boundary of the Alps ("Alpen-Südrand").

The depth of the Moho along the axis of the Eastern Alps under the "Hauptkamm" was determined by measurements along the *A*lpine *L*ongitudinal *P*rofile (*ALP* 1975) from France to Hungary. The *ALP* 1975 followed the axis of the Eastern Alps from the Swiss/Austrian border to a point west of Graz. In the middle part of the *ALP* (under the Hohen Tauern in particular) the Moho lies about 50 km deep for a distance of nearly 500 km. From west of Graz the depth of the Moho decreases as one goes eastwards. At the Austrian/Hungarian border the depth has reduced to about 25 km (Alpine Explosion Seismology Group, reporter H. Miller 1977). It has been known for a long time that the Moho is fairly shallow under the Hungarian basin.

Two low velocity zones for *P*-waves were found by the *ALP* experiment. They are a more than 10 km thick layer between about 20 and 33 km (the velocity changing with increasing depth from 6.2 to 5.6 to 6.8 km/s) and a thinner lower layer between 40 and 45 km (velocity changing from 6.9 to 6.3 to 6.9 km/s). While the upper thicker layer could be found, at changing depth and with variable thickness under the "Hauptkamm" (almost along the whole length of the profile), the deeper low velocity zone was found only under the Hohen Tauern (Tauern-Fenster).

Structures under the Moho

From the measurements along the *ALP* it was found that the *P*-wave velocity below the Moho is relatively high, for example v_p increases about to 8.4 km/s at a depth of 60 to 70 km (H. Miller, personal communication 1979). Similarly high velocities were also indicated by a study of the travel time residuals in the Eastern Alps (Brüstle 1979). A travel time residual is the observed travel time of a seismic wave minus the theoretical travel time of the same wave in a standard earth model. Brüstle calculated the residuals at two stations, at Schlegeis ("Zillertaler Alpen") and at Gräfenberg ("Fränkischer Jura"). He used the observations of waves arriving from different directions at these stations from distant earthquakes. (The distances to the earthquake location were more than 3000 km!) As the structure of the crust under both stations is known from seismic refraction experiments, the travel time through the crust could be calculated. It was possible therefore to eliminate the influence of the different structures of the crust below the two stations. The differences between the two residuals reduced in this way were interpreted in terms of differences in the structure of the upper mantle. Brüstle produced the following model: Under Schlegeis in the centre of the Eastern Alps the asthenosphere, if it exists at all, is very thin and the upper surface of the olivine-spinel zone has an upward bulge of about 75 km compared with the upper mantle under Gräfenberg in the mesozoic Tafelland. - This conclusion and the above mentioned high *P*-wave velocity can be explained by a tongue of cold material dipping steeply to the south (a subduction zone perhaps). This model is compatible with one of the results of the thermodynamics of convection: phase boundaries lie higher in a region of downward flow than in the surrounding material, and vice versa in a rising flow. Because of the lack of deep-focus earthquakes it is usually considered that there is no active subduction under the Eastern Alps today. The kind of measurements described above do not give any information which can tell us, if this structure of the upper mantle is an active subduction zone or a relic of an earlier subduction.

Kinematics of the Northern Calcareous Alps

Because the deepest part of the Molasse trough lies south of the "Alpen-Nordrand" it could be expected that the northern part of the Northern Calcareous Alps is moving downwards. On the contrary the southern part of the Northern Calcareous Alps belongs to the uplift area of the Central Alps. Therefore the Northern Calcareous Alps, sliding over their basement, are moving northwards against the unconsolidated material of the Molasse trough, while at the same time the whole mechanism moves northwards.

Solid-state convection in the rocks under the Eastern Alps

Two-dimensional models of steady solid-state convection in the rocks under the Eastern Alps have been calculated by the author in order to gain a better understanding of the kinematics and dynamics of the processes occurring there. Because the flow is not steady such models can, of course, only be approximations.

Numerical solutions were found for the following set of differential equations: 1. The mechanical force balance. (The sum of all forces and moments acting on an element of the material must be zero.) 2. The continuity equation (conservation of matter). 3. The mechanical response of the material. As an approximation the rock was taken to be a viscous liquid with effective viscosity η. For the first models it was assumed that the nonlinear behavior of the rocks is averaged out by many small earthquakes and very many micro-earthquakes which occur in periods of several tens of thousands years within volumes of some cubic kilometers. In a second generation of models it will be assumed that the deviatoric stresses suddenly drop when an upper stress limit is reached. This will be done to take into consideration the nonlinear rheology of the rocks. It is advantageous for this problem to keep the various physical phenomena, and therefore equations, separate and not combine them in the Navier-Stokes equation.

The following boundary conditions were put into the models: a) At the surface the tangential and vertical components of stress are zero. b) Values of the flow rate $\vec{v}$ $(x, 0)$ at the earth's surface $(z = 0)$ were deduced from observations of the surface or near surface structures. Because of the possibility of numerical instabilities in the technique so far developed for the treatment of this problem, the flow vector $\vec{v}$ could be calculated only down to depths about twice as great as the spacing between surface points at which a velocity was given. c) A density distribution taken from seismic and gravimetric models of the crust was fed into the equations. d) A viscosity distribution was taken which allowed both horizontal and vertical variations of η. The effective viscosity at and close to the earth's surface was taken to be small because of the large number of fractures per volume unit. The viscosity was assumed to be greatest in the upper or in the middle or in the lower crust (sklerosphere) and decreases again in the upper mantle, reaching a minimum in the asthenosphere.

These methods to calculate the flow under the surface of the earth can be extended to models of nonsteady and three-dimensional solid-state convection, but with a great increase in the computing time required. So far only two-dimensional models of steady flow under the Eastern Alps of regional and local extent, ignoring the heat transport, have been calculated and a vertical cross section of the flow vectors have been produced and will be published shortly.

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