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PREFACE

The leading scientists in the many different fields of geology were invited by the Organizing Committee to present a paper on a specific problem in present-day geological science at the 27th International Geological Congress. The published proceedings of the Congress consist of twenty-three volumes. Each volume is dedicated to a particular aspect of geology. Together the volumes contain all of the contributions presented at the Congress.

The Organizing Committee is pleased to acknowledge the efforts of all of the participating scientists in helping to produce these proceedings.

Professor N. A. BOGDANOV
General-Secretary of the
Organizing Committee

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SEISMIC ANISOTROPY AND COMPOSITION OF THE CONTINENTAL SUBCRUSTAL LITHOSPHERE

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ABSTRACT

Petrological models for the upper mantle predict isotropic velocities for P-waves which contradict seismic observations unless seismic anisotropy is taken into account. The range of petrological models compatible with the observed azimuthal variation of P-wave velocity is explored. The azimuthal distribution of amplitudes of mantle phases and the observed increase of P-velocity with depth both indicate a contribution of anisotropy with depth together with an increase of preferred orientation. Even depletion of the upper mantle in basaltic components as suggested by mantle xenoliths from various parts of Germany, cannot explain the velocity depth and azimuthal amplitude observations without an increase of anisotropy with depth.

Preferred orientation is the most likely mechanism for the observed phenomena. In Southern Germany its fast a-axis at the Moho is directed towards N22°E. Also the b-axis is required to be horizontal. This orientation places the vertical b-plane into the direction of maximum horizontal shear stress deduced from fault-plane solutions of earthquakes. This observation could indicate a recent formation of anisotropy in the continental subcrustal lithosphere.

1. INTRODUCTION

The upper mantle between the Mohorovičić and the lithosphere-asthenosphere boundaries has been considered by seismologists for a long time as a rather homogeneous

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layer where velocities of P- and S-waves change only slightly with depth along a geotherm and with little lateral variations. Analysis of P- and S-wave travel-times (e.g. Jeffreys and Bullen, 1935) and dispersion of surface waves (e.g. Knopoff, 1972) from earthquakes observed at widely sparated seismological stations had contributed to this simple model of the subcrustal lithosphere.

Deep sounding of the upper mantle by controlled source seismic refraction experiments, especially on long-range profiles changed this model of the subcrustal lithosphere drastically. The most important findings are unusually high P-wave velocities between 8.5-8.7 km/s at rather shallow depth in the upper mantle. The vertical gradients of the P-velocity range from 5 to 30 $10^{-3}s^{-1}$. The strongest gradients have been observed in Southern Germany (Fuchs, 1979,1980; Fuchs et al., 1981; Fuchs and Vinnik, 1982). Bamford (1973,1977) deduced an elastic anisotropy of the topmost amntle of 7-8% from a time-term analysis of P_n-arrivals. This is as large as previously detected in the oceanic mantle of the Pacific (Raitt et al., 1969). It will be shown that both observations - P_n anisotropy and high velocities with strong gradients - are related to each other.

Anisotropy of the upper mantle has been postulated by petrologists from the study of olivine in mantle xenoliths and lherzolite massifs (e.g. Nicolas et al., 1971, 1972; Peselnik et al., 1974). Both from field observations and laboratory experiments the fabrics and mode of preferred orientation of olivine was investigated (e.g. Nicolas et al., 1971). It appears that the fast a-axis of olivine is oriented nearly parallel to the flow lines of upper mantle material and that the b-plane assumes an orientation parallel to its foliation planes. Therefore, the question arises whether the fabrics of olivine derived from mantle xenoliths and from lherzolite massifs is typical for the continental mantle on a regional scale or whether it is restricted to a few anomolous pockets. It must also be asked whether the seismic anisotropy derived by Bamford (1973) for the topmost part of the continental mantle is a feature restricted to the immediate neighbourhood of the crust-mantle boundary.

This paper advances new evidence for elastic anisotropy in the continental subcrustal lithosphere of Southern Germany and compares it with predictions of seismic velocities from petrological models. It will be shown that the anisotropy increases with depth and extends to a depth of at least 50 km. The evidence leading to an anisotropic model of the upper mantle in Southern Germany is coming (1) from the azimuthal variation of the P_n-velocities (Bamford 1973,1977), (2) from the azimuthal distribution of amplitudes of P-mantle phases and (3) from the depth-velocity distribution on a reversed long-range profile (Steinbrunn-Böhmischbruck (SB-09); see Fig.5) in Southern Germany (Ansorge et al., 1979; Stangl, 1983). Avery likely kind of anisotropy fitting observations and perological models has the fast a- and slow b-axis of olivine both in a horizontal plane. The vertical b-plane, which is also a preferred glide plane of olivine (nicolas and Poirier, 1976) coincides almost perfectly with the vertical plane of maximum shear stress in the crust of Germany. This correlation is indicative of a recent process of preferred orientation of the olivine in the upper mantle of Southern Germany. The increase of velocity with depth can only partially be explained by a depletion of the upper mantle pro gressing with depth, rather the high velocities progressively attained at depth require anisotropy increasing with depth. The interaction of stressfields in the subcrustal lithosphere induced both from the crust and from the lithosphere-asthenosphere boundary is discussed.

2. PREDICTION OF SEISMIC P-VELOCITIES FROM PETROLOGICAL MODELS OF THE UPPER MANTLE

Petrological models of the upper mantle in conjunction with laboratory experiments on seismic velocities and their pressure/temperature derivations allow to predict independently the seismic velocities at that depth where they have been measured "in-situ" by deep seismic sounding (Hirn et al., 1977; Faber, 1978; Leven et al., 1981). Discrepancies between observed and predicted seismic velocities can constrain physical and petrological parameters, such as temperature, state of anisotropy and modal compositions of petrological models.

In the first part of this chapter, the isotropic P-velocity-depth distributions for various modal compositions of the upper mantle are predicted along two geotherms - (1): temperature proposed for SW-Germany (Werner and Kahle, 1980) and (2): low temperatures for the Precambrian Shield (Ringwood, 1969). Both geotherms are depicted in Fig. 1 together with a P, T, Z-diagram for mineral assemblages in pyrolite for the upper mantle (Green and Ringwood, 1967). Table I gives the modal compositions for Spinel- and Garnet-Pyrolite and for mantle xenoliths from various locations in Western and Southern Germany. The Surface Temperature Pressure (STP) velocities with their partial derivatives of the various components are listed in Table II together with the corresponding velocities at various points along the geotherm (1) for Southern Germany. The values for the P- wave velocities, their pressure and temperature derivatives have been taken from the quoted literature. It is understood that there are values reported by other authors which deviate from those used in this paper. However, their choice would not affect the main conclusions in this paper. The velocity-depth distributions for the petrological models listed in Table I are depicted in Fig. 2 together with the observed P-velocities inverted from the travel time data on profile SB-09 in Southern Germany (see Fig.6). Three features are quite obvious: (1) except for the low velocity zone (LVZ) between 35 km and 46 km all predictions from petrological models fall below the observed velocities; (2) all petrological predictions possess negative velocity gradients from 25 km to more than 50 km while the observations have two zones with strong positive velocity gradients; (3) in the LVZ the prediction of model WE (Western Eifel) comes very close to the observed velocities.

The discrepancies between observed and predicted velocities amounting to 0.3-0.5 km/s cannot be resolved by a lowering of temperature. Even along the Precambrian Shield geotherm (2) the velocities increase only by about 0.04 km/s compared to those along geotherm (1), and the gradients still remain negative.

OBSERVATION OF P_n- ANISOTROPY IN SOUTHERN GERMANY

The existence of anisotropy of P_n-waves in the continental upper mantle was first discovered by Bamford (1973) during a time-term analysis of P_n-phases in Southern Germany. In the more refined MOZAIC time-term method applied to the same set of observations Bamford (1977) obtained a number of fits which have been plotted in Fig.3 together with the observed data. The fastest direction is N22.5°E.

4. FIT OF ANISOTROPIC PETROLOGICAL MODELS TO SEISMIC OBSERVATIONS OF TRAVEL TIMES IN SOUTHERN GERMANY

From chapter 2 it is evident that isotropic velocities predicted from petrological models do not match the velocities in the continental subcrustal lithosphere as observed on seismic long-range profiles. In the next part an attempt will be made to match the observed anisotropy of the P_n-mantle phase in Southern Germany (Bamford, 1973) to petrological models.

The azimuthal velocity-distribution $v(\phi)$ of a petrological aggregate based on a net travel-time argument is computed from:

$$1/v(\phi) = \sum_{i=1}^{L-1} a_i/v_i + (1-r)\cdot a_{OL}/v_{OL} + r\cdot a_{OL}/\tilde{v}_{OL}(\phi) \quad (1)$$

where a_i is the volume percentage and v_i the isotropic velocity of the i^{th} isotropic constituent of the aggregate; a_{OL} is the percentage of olivine and V_{OL} its isotropic velocity; L-1 the number of isotropic constituents without olivine, r is the percentage of olivine with preferred orientation and $\tilde{v}_{OL}(\phi)$ the azimuthal distribution of the anisotropic P-velocity of olivine in a horizontal plane, where $\phi = 0$ is the direction of the maximum velocity:

$$\tilde{v}^2_{OL}(\phi) = A + C \cdot \cos 2\phi + E \cdot \cos 4\phi \qquad (2)$$

The A,C,E in Eq. (2) are computed from the elements $\tilde{C}_{ij}$ of the elasticity tensor and their partial derivatives and density for various depths along the geotherm for Southern Germany.

A systematic search for petrological models consisting of Olivine (OL), Orthopyroxene (OPx), Clinopyroxene (CPx) and Spinel (SPi) which are compatible with the azimuthal velocity distribution (v_{max} = 8.31 km/s, v_{min} = 7,73 km/s) derived by Bamford (1973,1977) is undertaken in this chapter.

We will not only change the modal composition but also the orientation of the olivine crystals, i.e., we will also consider a horizontal orientation of the c-axis, dip the fast a-axis with respect to the horizontal and further more consider a random orientation of the b- and c-axis in girdles around the a-axis forming a transversly isotropic medium.

A petrological model may be visualized as an aggregate consisting of a_{OL}% olivine and of $(1-a_{OL})$% isotropic components (without olivine). r% of the olivine has a preferred orientation, i.e., $(1-r)a_{OL}$% of the olivine is also isotropic with a velocity V_{OL}. The isotropic velocity v_O of the rest of the aggregate without olivine and the amount of preferredly oriented olivine required to match the observation (v_{max},v_{min}) has to be determined (anisotropic olivine has only two maxima and two minima in its azimuthal velocity distribution).

The compositions compatible with Bamford's (1977)

$$v_{max} = 8.31; \; v_{min} = 7.73 \text{ km/s}$$

have been computed and depicted in an CL-OPx-CPx triangle in Fig.4. These diagrams show also the compositions (R) and of xenoliths from Germany (1)- (5) (see Table 1).

The area surrounded by the thick solid line (Fig.4) corresponds to those modal compositions with the appropriate preferred orientation of olivine for which the velocities are compatible with Bamfords v_{max} and v_{min} for an orthorhombic crystal with horizontal b-axis. The dashed line surrounds the area corresponding to a transversly isotropic texture with random (b,c)-girdles. The case of a horizontal c-axis cannot fit the observations. The thin parallel lines designate equal SPi-content within the compatibility area. Below the hatched line a preferred orientation r more than or equal to 100% would be required.

For $\Theta = 0°$ Ringwood's Spinel-Pyrolite (R) lies outside the range of compatibility (ROC) for both horizontal b-axis and for the transversly isotropic model. However, it is closer to the range of horizontal b-axis with SPiO than the German xenoliths. The modal compositions of the xenoliths in Germany are clearly dpleted in basalt compared to the ROC. The ROC for transversly isotropic models is much smaller than that for the horizontal b-axis, and it requires only a very small content of CPx and SPi (smaller than 10-20%).

If the direction of flow in the continental upper mantle causing the preferred orientation is nearly horizontal the direction of the a-axis is also horizontal. Under this assumption the proposed petrological models are not compatible with the seismic anisotropy observations. Therefore, the modal compositions have to be changed. Yhe various possible models in the ROC for $\Theta = 0°$ cannot be distinguished by the seismic data. In the following form the ROC for z = 25 km, $\Theta = 0°$ a representative modal composition M1 with an orthorhombric fabric (b-axis horizontal) has been selected: OL50, OPx45, CPx4, SPi1 with 61.8% preferred orientation. Model M1 was selected in such a way that the OL-content is not less than 50% and that SPi is 1%.

No match can be obtained for an orthorhombic fabric with a horizontal c-axis. This indicates that the b-plane cannot be horizontal at z = 25 km. In the model M1 with horizontal b-axis the b-plane is vertical. Although there is a small ROC for a transversly isotropic fabric ((b,c)-girdles) with little CPx-content this fabric will not be pursued because no mantle xenoliths with (b,c)-girdles

in olivine are reported for Germany.
Due to the uncertainty of depth, the influence of a change in depth on the position of the ROC has been investigated. If Bamford's v_{max} and v_{min} had been observed at a depth of 30 km instead of 25 km the ROC would move by about 1% towards higher OL-content. Therefore, the depth-uncertainty does not significantly influence the modal compositions in the ROC.

5. CONTINUATION OF PETROLOGICAL MODELS TO DEPTH

Now an attempt will be made to search for the continuation of the petrological model M1 representing the ROC at a level z = 25 km to larger depths using seismological information as a guide. In a first step the depth-velocity distribution (Fig.2) derived on theprofile Steinbrunn-Böhmischbruck (SB-09) (See Fig. 5) with an azimuth N62.5° E will be applied in a search for compatible petrological models. Later on, amplitudes of mantle phases along refrac tion seismic profiles in Southern Germany in various azimuths will be used as an additional discrimant.
The azimuth N62.5°E of the profile SB-09 deviates by 40° from the fast direction N22.5°E of Bamford's optimum fit II. The velocities in the azimuth of the SB-09-profile at 40° off the fast direction a) for the Bamford fit II b) for the compatible model M1 and c) the observed velocity at a depth of 25 km are 8.11, 8.03 and 8.10 respectively. Considering the uncertainty of the direction of Bamford's fast axis and of the velocity along the SB-09 profile these three values are considered to be matching within the error limits. To a first approximation along the SB-09-profile the velocity increases nearly linearly to a value of 8.425 km/s at a depth of 35 km (Stangl, 1983). Which petrological models can account for this velocity increase to this depth?
In chapter 2 discussing isotropic velocity-depth distributions it was shown that all proposed petrological models fail to account for the observed high velocity- and gradient-values. Even the depleted models (e.g. Western

Eifel, WE: OL73, POx19, CPx7, SPi1) reach isotropic velocities of only 8.10 km/s at z = 35 km. They all have negative velocity-depth gradients in the range z= larger or equal to 25 km and smaller or equal to 35 km (See Fig. 2). The increase of velocity with depth can only be explained if the anisotropy deduced for the topmost mantle at z=25 km continues to greater depths and increases its amount.

The question is whether an increase of anisotropy with depth alone can account for the velocity 8.425 km/s observed on the SB-09 profile at a depth of 35 km or whether a change in both the fabric and the modal composition is required. The family of modal compositions in the range of compatibility (ROC) in the direction of the SB-09 profile (N62.5°E, 40°E off v_{max}) at a depth of 35 km reach only values of about 8.06 km/s, even with 100% preferred orientation. Even with horizontal (a,c)-axes model M1 with 100% preferred orientation assumed only a velocity of 8.13 km/s at 40°E off v_{max} and z= 35 km. Therefore, there are only three possibilities to reconcile the petrological models with the seismic observations: a) a rotation of the fast a-axis around the vertical with depth; b) a change in modal composition; c) a combination of both. A clockwise rotation of the fast axis of olivine by about 22° would give 8.425 km/s at a depth of 35 km in the direction of the SB-09 profile without change of modal composition of M1 if 100% preferred orientation is assumed. However, a remarkable feature of this model with constant modal composition but horizontal rotation of the a-axis is the azimuthal distribution of the vertical gradients: The strongest positive gradient occurs now along the SB-09 profile ($+40.10^{-3}s^{-1}$), Bamford's fastest direction has a gradient of only $+6.10^{-3}s^{-1}$, and there are negative gradients in the azimuth ranges N285°E to N17°E and N105°E to N197°E. Vertical gradients of velocities are very closely related to amplitudes of seismic waves. It is most remarkable that the direction of strong and weak P_n amplitudes in Southern Germany coincides with the fast and slow direction of P-wave velocity respectively.

Since a continuation of model M1 to a depth of 35km with 100% preferred orientation of olivine would require a rotation of the fast a-axis by about 22°, the strongest positive gradients and, therefore the strongest amplitudes would occur along profile SB-09. This, however, has not been observed in Southern Germany (see Fig.5). Therefore, we must reject a continuation of model M1 by increasing the preferred orientation and rotating the a-axis horizontally around the vertical. A change in modal composition is the only possibility to keep the strong amplitudes centered around the fast direction N22.5°E.

Mantle xenoliths from various parts of Germany provide evidence for a strongly depleted mantle (see Table I). One typical modal composition from the Western Eifel (WE: OL73, OPx19, CPx7, SPi1) is clearly enriched in olivine (OL). The depth of these xenoliths is poorly defined; they are estimated to originate from depths shallower than 75 km (Sachtleben, 1980). If the composition WE is assumed at a depth of 35 km with 100% preferred orientation and the a-axis rotated by 3.5°E around the vertical the velocity of 8.425 km/s occurs in the azimuth N62.5°E (40°E off Bamford's fastest direction). This is the azimuth of the SB-09 profile and thus can be considered as a satisfactory match.

In the low velocity zone (LVZ) along the profile SB-09 the inverted velocity between 35 km and 46 km depth is 8.1 km /s. This coincides perfectly with the isotropic composition WE (8.1 km/s) without any preferred orientation of olivine. Therefore, it is concluded that the material in the LVZ may be isotropic and of WE modal composition.

6. DISCUSSION AND CONCLUSIONS

The "anvil"-model of anisotropic velocity distribution in Fig. 6 possesses some features which deserve further discussion. The observed depth-velocity distribution along the profile SB-09 has been marked by a thick dash-dotted line. There are zones of low horizontal velocity in the lid of the LVZ formed by the negative gradients. The LVZ between 35 km and 46 km with an isotropic velocity of 8.10 km/s is only a low velocity layer in the two sectors with positive gradients in the lid and becomes a zone with high velocities relative to the overburden in the range of negative gradients in the lid. Low velocity sectors occur also in the layer at the bottom of the LVZ, partly caused by the LVZ, partly by negative gradients in this layer.

The scheme of travel time curves and the corresponding record sections will change drastically form the fast to the slow azimuth. In particular the layer of the LVZ, invisible in the fast direction, will produce a refracted arrival in the slow direction. This requires further studies and will be presented in a forthcoming paper.

The present analysis of explosion seismic and petrological data has provided evidence that both sets can constrain each other. However, this analysis can be improved, if certain defaults of the seismic data can be overcome. The present data do not contain any common-depth point observations, that is an observation scheme where an upper mantle area is traversed jointly, in at least three azimuths by seismic waves. Furthermore, it appears that the azimuthal distribution of amplitudes is much more sensitive to the anisotropic velocity-depth distribution than the travel times. Especially the aperture of the sectors with strong amplitudes and weak amplitudes and their orien tation with regard to the fast direction of the P_n-phase contain important information on the depth-dependence of the elements of the elasticity tensor.

The shallow occurrence of high velocities and large velocity-depth gradients in the subcrustal lithosphere of Southern Germany offers a unique possibility to define more precisely the type of anisotropy and its mechanism of generation. The presently available observations are by no means perfect. Quite a number of azimuths is not covered by the existing seismic refraction profiles in Southern Germany for depths below 30 km the azimuthal coverage is extremely poor and urgently needs improvement. A common-depth point experiment with reversed long-range profiles in Southern Germany is proposed to solve some of the open questions. The interpretation of the observation from such an anisotropy experiment must be supported by theoretical investigations of wave propagation in anisotropic media with depth-dependence elements of the elasticity tensor.

The question arises whether the anisotropy detected in