EXPLANATION OF THE ANOMALOUS ENERGY PROPAGATION OF EAST ALPINE TRANSVERSAL QUAKES

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1. Introduction

In the 19*th* century at the latest it was known that the energy of strong earthquakes in the Northeastern Alps propagates preferably to the north and northwest, which means transverse to the mountain-range of the Alps. Due to this fact Eduard Suess (1873, 1875) and his contemporaries designated these earthquakes as „Transversal Quakes". They tried to explain the anomaly of energy propagation by a „Shock-line hypothesis". As a rule, shock-lines were identical with the major axes of the extended shaken areas, the shapes of which are nearly elliptical, and the epicentres lie nearby the southern foci. — Not least the circumstance that the energy of strong East Alpine earthquakes propagates far into the Bohemian Massif is a reason for a cooperation of Czechoslovak and Austrian seismologists for many years.

2. Description of the problem

The foci of strong transversal earthquakes are mainly located on steeply incident faults of the Peripieninic Lineament (cf. Zátopek and Beránek, 1975), that means, along the Mur-Muerz-Line, in the Semmering region as well as in the Vienna Basin, but also on the East Alpine Northern Rim Fault (cf. Drimmel, 1980a) and on faults running about parallel to and lying in between the fault systems mentioned before (cf. Drimmel and Procházková, 1985; Heritsch, 1918; Procházková and Drimmel, 1983). The macroseismic focal depths of strong transversal quakes mostly lie within the interval of 8 to 12 km, in the Semmering region also between 15 and 20 km (cf. Drimmel, 1980a).

(Remark: The „macroseismic focal depth" is the depth of the virtual seismic point source which in calculations frequently takes the place of the finite source size. The macroseismic focal depth is always smaller than the depth of the centre of gravity of a steeply incident fault-plane.)

Transversal quakes do not only have the characteristic to radiate their energy mainly to the north and northwest, but they also cause a distinct increase of the seismic intensity in larger epicentral distances, so that, for example, in Southern Bohemia, far away from the epicentral damaged area, local damages occur again (cf. Kárnik et al., 1957; Procházková, 1974).

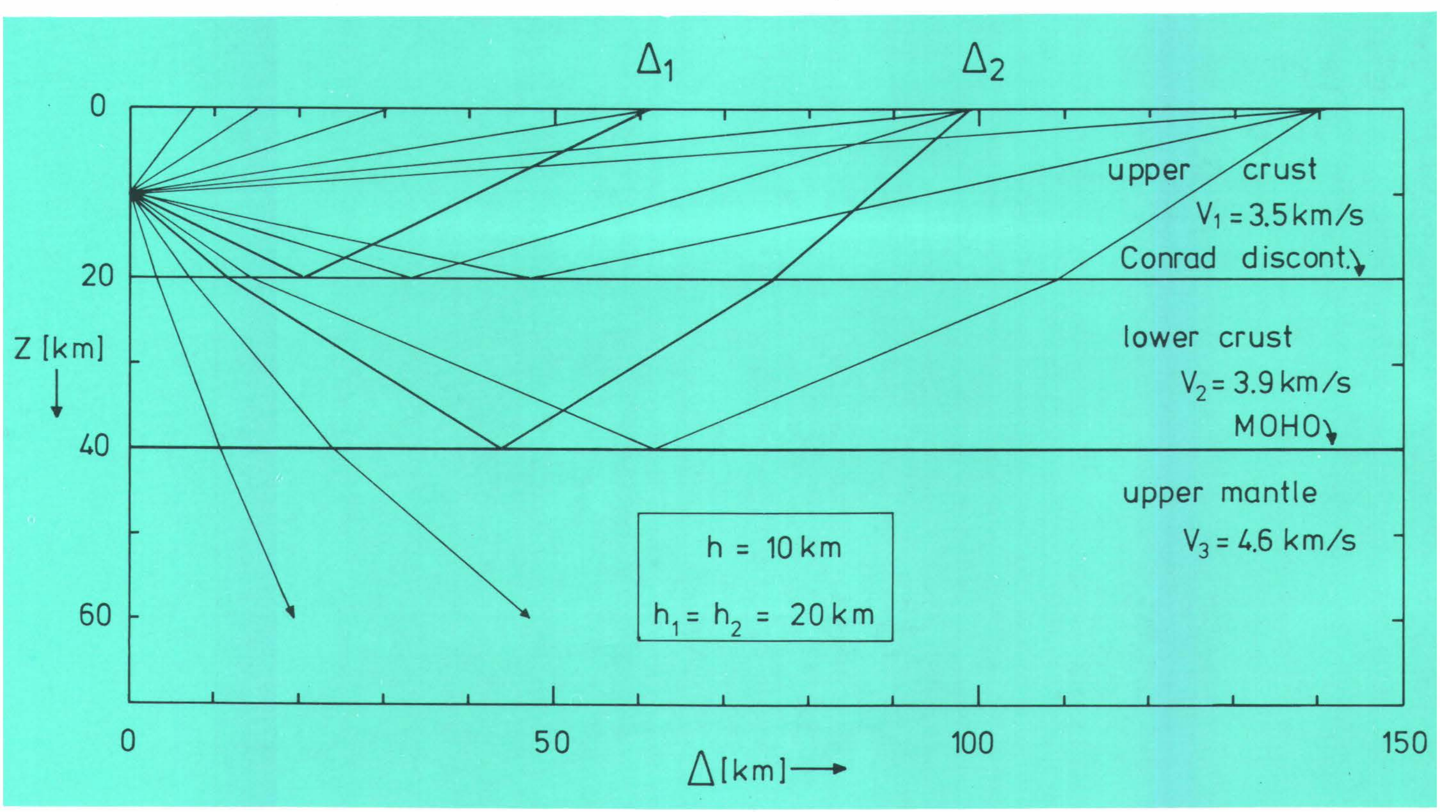
Whereas our predecessors had worked with the shock-line hypothesis, our generation tried to explain the propagation anomaly of transversal quakes by the aid of new findings about structure of the Earth's crust and the depth-dependence of seismic wave velocities; especially the discovery of low-velocity layers has influenced our reasoning enduringly. — The assumption of a channel for seismic energy can certainly explain special cases of anomalous energy propagation (cf. Drimmel and Duma, 1974), as model seismic experiments have also proved (cf. Drimmel et al., 1973), but the general case of transversal quakes can definitely be explained without this assumption. The proof for this allegation follows in the next section.

3. The reason for transversal quakes

Before we can explain the propagation anomaly of transversal quakes we have to study the regular propagation of seismic waves in a two layer model of the crust. — As the S-wave energy of near earthquakes is about 100times bigger than the P-wave energy (cf. Duda, 1965), we can neglect the P-wave energy in our investigation.

We take into consideration the increase of the velocity of seismic waves with growing depth by assuming an upper

Fig. 1: Two-layer model of the Earth's crust with a seismic point-source within the upper crust; paths of directly running as well as totally reflected shear-waves



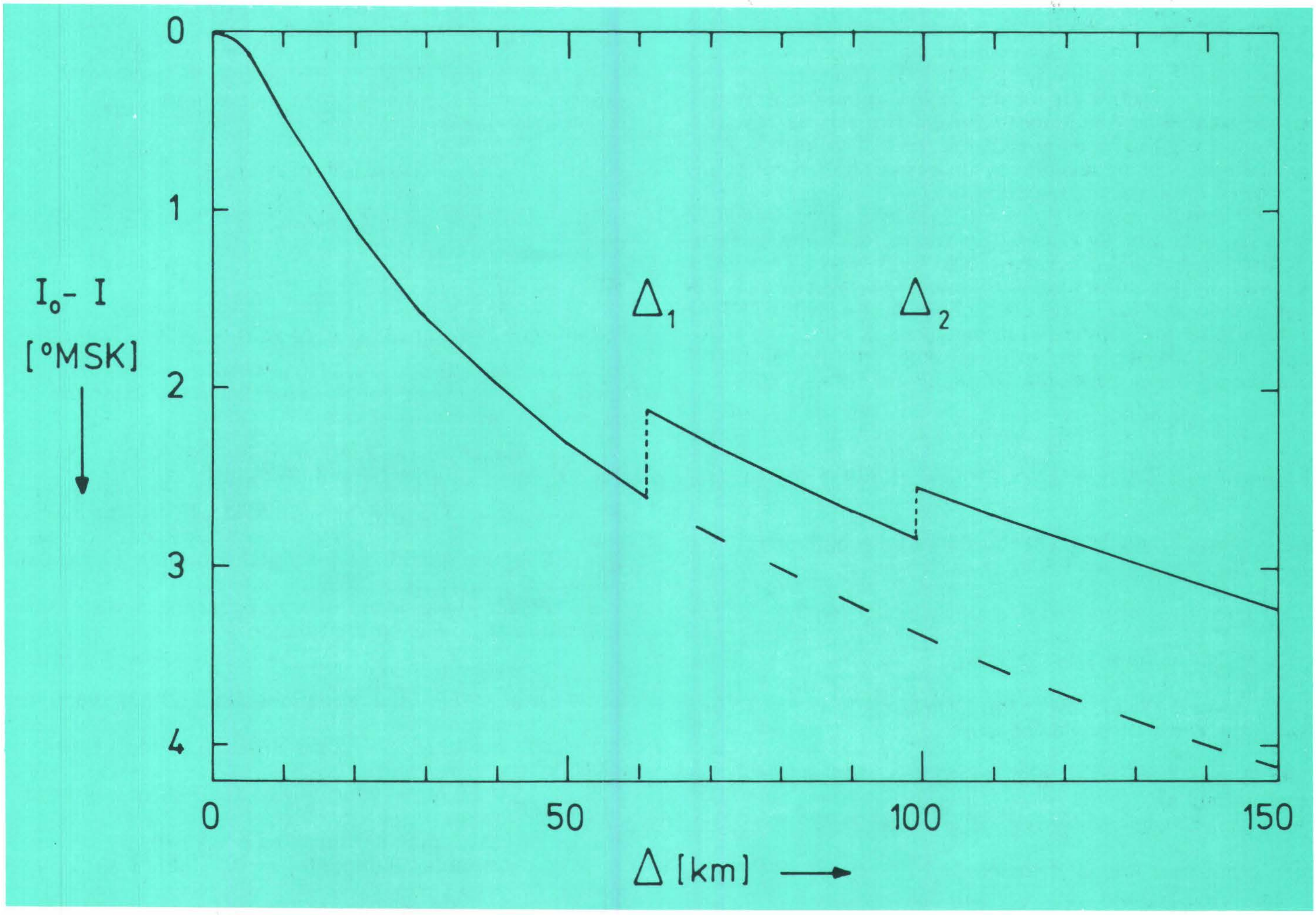
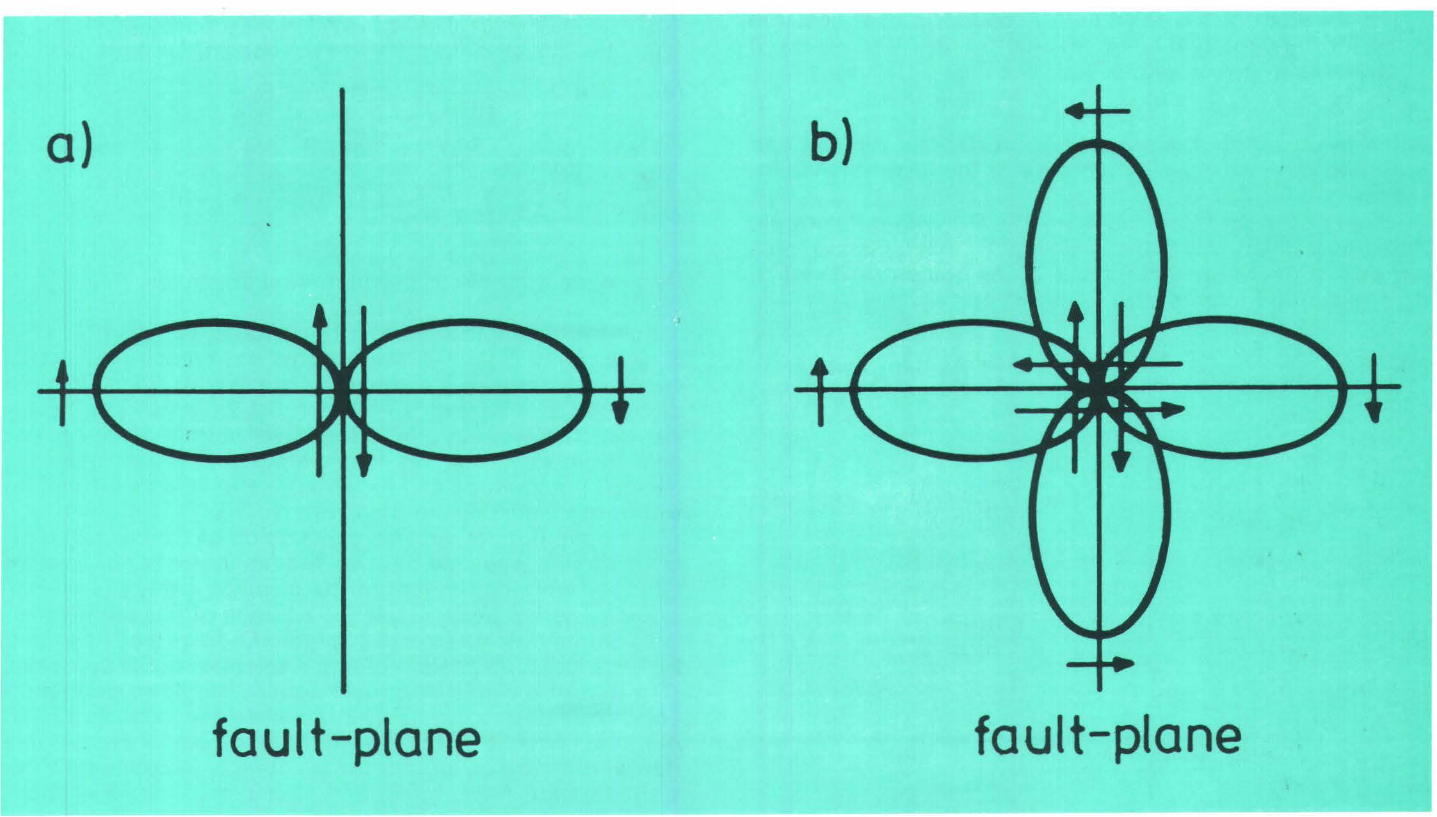


Fig. 2: Intensity-distance curve for the example reproduced in fig. 1., with $\kappa \doteq \bar{\kappa} \doteq 10^{-2}$ [km^{-1}]

▼ Fig. 3: Radiation of shear-waves
a) from a dipole with moment (single force couple);
b) from a double dipole (double couple) with zero net moment



and a lower crust with constant physical properties. The upper and the lower crust are separated by the „Conrad discontinuity", and the lower boundary of the crust is the „Mohorovičić discontinuity" (= MOHO). The seismic point source (with depth h) is located in the upper crust, corresponding to East Alpine earthquakes. The seismic rays originating from the focus obey to the laws of ray optics. In figure 1 the paths of seismic rays in case of horizontal boundaries of the crust are described.

As it can be learned from fig. 1, in epicentral distances $\Delta < \Delta_1$, only directly running Sg-waves reach the surface, in distances $\Delta \geqslant \Delta_1$, however, also $S_{Co}S$-waves (= by the Conrad discontinuity totally reflected Sg-waves) reach the surface. In addition, there are S_MS-waves (= by the MOHO totally reflected Sg-waves) in distances $\Delta \geqslant \Delta_2$. The following relations apply to the travel-times and epicentral distances of these waves (cf. Drimmel and Trapp, 1975):

$$t_{Sg} = (\Delta^2 + h^2)^{1/2}/v_1$$

$$t_{S_{Co}S} = [\Delta^2 + (2h_1 - h)^2]^{1/2}/v_1, \text{ with } \Delta = (2h_1 - h).\tan\alpha_1,$$

α_1 = angle of incidence at the Conrad discontinuity,
h_1 = thickness of the upper crust;

$$t_{S_MS} = (2h_1 - h)/v_1\cos\alpha_1 + 2h_2/v_2\cos\alpha_2, \text{ with}$$

$$\Delta = (2h_1 - h)\tan\alpha_1 + 2h_2\tan\alpha_2;$$

α_2 = angle of incidence at the MOHO,
h_2 = thickness of the lower crust.

The following formulae apply to α_2^*, the „critical angles" of total reflection.

$$\alpha_1^* = \arcsin(v_1/v_2),\ \alpha_2^* = \arcsin(v_2/v_3);$$

this yields the „critical distances"

$$\Delta_1 = (2h_1 - h).\tan\alpha_1^* \text{ and } \Delta_2 = (2h_1 - h).\tan\alpha_1' + 2h_2.\tan\alpha_2^*,$$
$$\text{with } \alpha_1' = \arcsin(v_1/v_3).$$

The duration of the maximum phase, δt_m, is almost the same for the directly running and for the reflected waves; if at observation points with $\Delta \geqslant \Delta_1$ the time differences $t_{S_{Co}S} - t_{Sg}$, $|t_{S_MS} - t_{Sg}|$, and $|t_{S_MS} - t_{S_{Co}S}|$ are smaller than or equal to δt_m, then a superposition of directly running and reflected waves causes an increase of the local seismic intensity.

In case of a spherical focus (radius R_1) with an isotropic radiation pattern, the seismic energy E_Δ, which is available per unit of the horizontal surface at the epicentral distance Δ, is given by the following relations:

$$(1)\quad E_\Delta = \frac{E_s}{4\pi\,(R/R_1)^2}\cdot\frac{h}{R}\cdot e^{-\kappa R}, \text{ for } \Delta < \Delta_1 \text{ [km], with } R = (\Delta^2 + h^2)^{1/2} \text{ [km]};$$

$$(2)\quad E_\Delta = \frac{E_s}{4\pi}\left[\frac{(h/R_1)}{(R/R_1)^3}\cdot e^{-\kappa R} + \frac{(2h_1\text{-}h)/R_1}{(R'/R_1)^3}\cdot e^{-\kappa R'}\right], \text{ for}$$
$$\Delta_1 \leqslant \Delta < \Delta_2 \text{ [km], with } R' = [\Delta^2 + (2h_1 - h)^2]^{1/2} \text{ [km]};$$

$$(3)\quad E_\Delta = \frac{E_s}{4\pi}\left[\frac{(h/R_1)}{(R/R_1)^3}\cdot e^{-\kappa R} + \frac{(2h_1 - h)/R_1}{(R'/R_1)^3}\cdot e^{-\kappa R'} + \frac{[2(h_1+h_2)-h]/R_1}{(R''/R_1)^3}\cdot e^{-\bar{\kappa}R''}\right],$$
$$\text{for } \Delta \geqslant \Delta_2 \text{ [km], with } R''\{\Delta^2 + [2(h_1 + h_2) - h]^2\}^{1/2} \text{ [km]};$$

E_s = total seismic energy, R = hypocentral distance
κ [km^{-1}] = absorption coefficient within he upper crust,
$\bar{\kappa}$ [km^{-1}] = mean absorption coefficient within the crust.
It is plausible that the seismic effects at the surface, W, are proportional to the available seismic energy, E_Δ (cf. Drimmel, 1980b; 1984):

$$(4)\quad W \sim E_\Delta/E_1 \qquad (E_1 = \text{unit of energy});$$

for the macroseismic intensity, I, is the logarithm of W, we get

$$(5)\quad I = \log_{10}(E_\Delta/E_1) + \text{const.}$$

For epicentral distances $\Delta < \Delta_1$ with equation (1) we get

$$(6)\quad I = \log_{10}(E_sE_1) - 3.\log_{10}(R/R_1) + \log_{10}(h/R_1) - 0.4343q.\kappa.R + \text{const; for } R = h \text{ follows the epicentral intensity } I_0:$$

$$(7)\quad I_0 = \log_{10}(E_s/E_1) - 2.\log_{10}(h/R_1) - 0.4343.\kappa.g + \text{const;}$$

the difference of equ. (7) and (6) yields

$$(8)\quad I_0 - I = 3.\log_{10}(R/h) + 0.4343.\kappa.(R\text{-}h), \text{ for } \Delta < \Delta_1 \text{ [km].}$$

This is a slightly modified Kövesligethy formula (cf. Kövesligethy, 1907; Sponheuer, 1960).
If we replace the seismic energy E_s by the surface-wave magnitude M_s, by using the relation

$$(9)\quad \log_{10}(E_s/E_1) = 1.5.M_s + \text{const,}$$

(cf. Richter, 1958), the equations (6) and (7), valid for $\Delta < \Delta_1$, turn into

$$(6')\quad I = 1.5.M_s - 3.\log_{10}(R/R_1) + \log_{10}(h/R_1) - 0.4343.\kappa.R + \text{const and}$$

$$(7')\quad I_0 = 1.5.M_s - 2.\log_{10}(h/R_1) - 0.4343.\kappa.h + \text{const.}$$

In case of East Alpine earthquakes it is valid

$$\text{magn}(\kappa) \doteq \text{magn}(\bar{\kappa}) \doteq 10^{-2}\ [km^{-1}]$$

and

$$\text{const} \doteq 1.9 \text{ for a twelve-grade intesity scale.}$$

Analogous to the intensity formulae for direct running waves we get the following intensity formulae for a distinct superposition of direct running and reflected waves:

$$(10)\quad I = 1.5.M_s + \log_{10}(F_1 + F_2) + \text{const, for } \Delta_1 \leqslant \Delta < \Delta_2 \text{ [km], with } F_1 = \frac{h/R_1}{(R/R_1)^3}\cdot e^{-\kappa R} \text{ and } F_2 = \frac{(2h_1 - h)/R_1}{(R'/R_1)^3}\cdot e^{-\kappa R'};$$

$$(11)\quad I = 1.5.M_s + \log_{10}(F_1 + F_2 + F_3) + \text{const, for } \Delta > \Delta_2 \text{ [km],}$$

$$\text{with } F_1, F_2 \text{ as before and } F_3 = \frac{[2(h_1+h_2)-h]/R_1}{(R''/R_1)^3}\cdot e^{-\bar{\kappa}R''}.$$

By that we are able to calculate real examples.

For the example which is reproduced in figure 1, with $\kappa \doteq \bar{\kappa} \doteq 10^{-2}$ [km^{-1}], we receive an intensity—distance curve with steplike increases of intensity at the epicentral distances $\Delta = \Delta_1$ and $\Delta = \Delta_2$ (cf. fig. 2), which are, however, practically always smoothed over certain distance-ranges. (Remark: From this result follows that macroseismic values of magnitude and focal depth should only be evaluated from macroseismic data with $\Delta < \Delta_1$.)

We have not yet won an explanation of transversal quakes with this, because the two sudden increases of seismic intensity are independent of the azimuth if there is an isotropic radiation pattern, but the solution of our problem results immediately from our former findings and the fact, that the radiation pattern of a real seismic source coincides with that of a single or double couple (single or double dipole; the latter is probably predominating; see fig. 3; cf. Aki, 1967; Schick, 1972), that the fault-planes of East Alpine transversal quakes altogether are steeply incident south to southeast (cf. Prey, 1980), and finally, that the local topo-

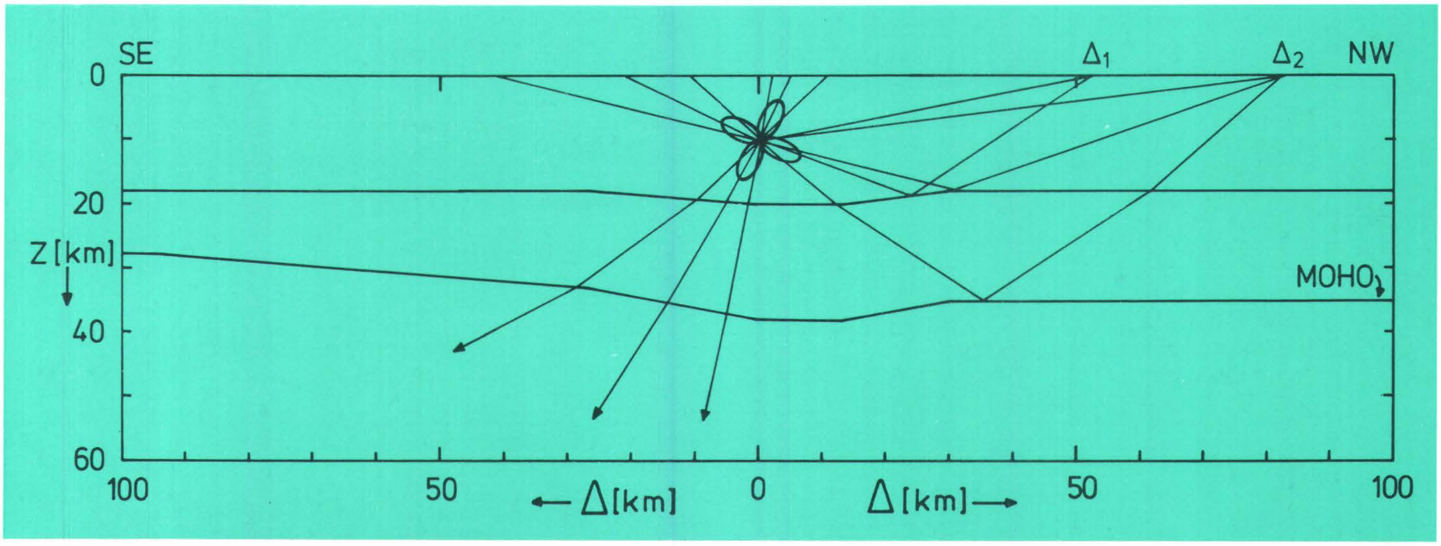
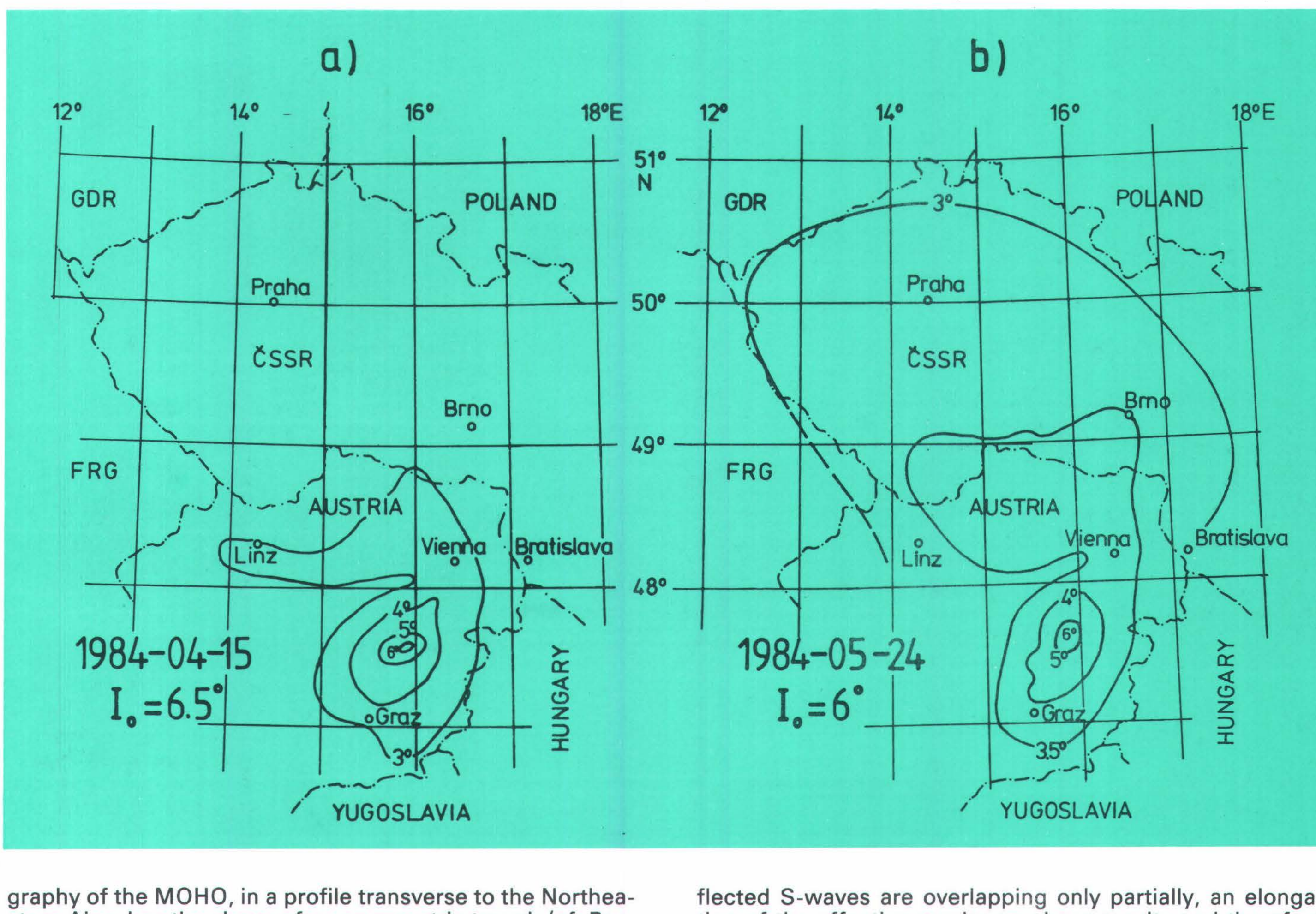


Fig. 4: Profile transverse to the Northeastern Alps (very simplified) with a seismic point source within the upper crust and the paths of directly running as well as reflected shear-waves

Fig. 5: Two earthquakes in the Semmering region with conspicuous differences in the shapes of their isoseismals
a) April 15, 1984: h = 5...7 km, I_0 = 6.5° MSK, M = 4.0 (macro);
b) May 24, 1984: h = 10...12 km, I_0 = 6° MSK, M = 4.1 (macro) ▼



graphy of the MOHO, in a profile transverse to the Northeastern Alps, has the shape of an asymmetric trough (cf. Posgay et al., 1988). In the northwest quadrant this constellation leads to a predominating radiation of shear-wave energy from the focus slanting downwards into the Bohemian Massif, where it suffers a total reflection on the Conrad and Mohorovičić discontinuity, if the angles of incidence exceed certain values; it emerges not before Bohemia, where it causes a distinct increase of seismic intensity. Owing to the fact that the maximum phases of direct running and reflected S-waves are overlapping only partially, an elongation of the effective maximum phase results and therefore resonance effects are possible there, too. — In the direction of Hungary, however, there is a normal decrease of seismic intensity because the seismic energy radiated from the focus slanting downwards carries through the Conrad and Mohorovičić discontinuity (see fig. 4). That's why the southern part of the shaken area has a normal shape. — Herewith we have the requested explanation of transversal quakes.

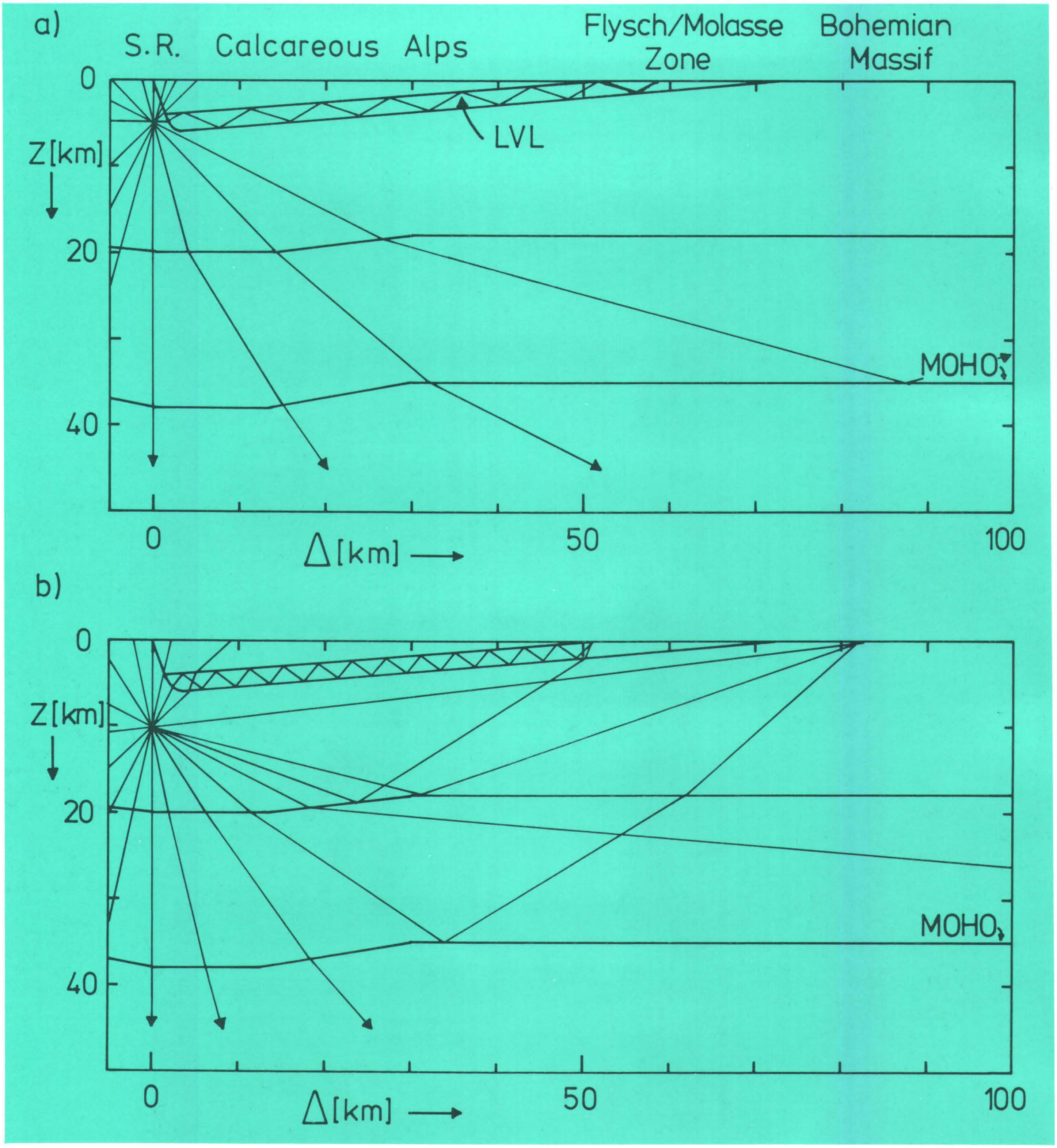


Fig. 6: Explanation of the different propagation of the investigated earthquakes (see fig. 5); a) h = 5 km; b) = 10 km

4. An Experimentum Crucis

A sequence of earthquakes happened in the Semmering region in 1984, two of which (April 15th, May 24th) caused slight damages in the epicentral area. The macroseismic investigation of these quakes yielded identical epicentral coordinates and nearly equal magnitudes, but conspicuous differences in the focal depths as well as in the propagation of the seismic energy to the north (see fig. 5). These differences of propagation could not be explained up to now, and at first sight, it looks as if our theory on transversal quakes failed, too. Therefore the attempt to explain the differences in the energy propagation of these earthquakes carries the weight of an „experimentum crucis".

From the first it can be stated that the earthquake on May 24, 1984 (fig. 5b) corresponds to a transversal quake, the propagation anomaly of which can principally be explained. Therefore it remains to explain the question why the quake of April 15, 1984 was not perceptible in Bohemia though it had the magnitude of the quake of May 24th.

If we suppose that our explanation of transversal quakes is true, then we will have to look for the reason for the propagation differences only in the different focal depths and in the marked deviation of the local geology from our very simple model of the crust.

As it turns out, it is enough to vary our model only in one detail, namely by the introduction of a thin low-velocity layer (= LVL) slightly dipping from north to south (see fig. 6). This LVL corresponds to a stratum of Molasse and Flysch between the Calcareous Alps (above) and the crystalline of the Bohemian Massif. The shear-wave velocity within the LVL is considerably smaller (ca. $v_1/2$) than that of the other geological units within the upper crust (ca. v_1), therefore in this connection we can calculate with only two different shear-wave velocities within the upper crust.

How to draw from figure 6a, in case of earthquakes in the Semmering region with small focal depths (5 km ±) the seismic energy radiated from the focus slanting downwards to the north will be captured by the LVL and led to the surface in the Molasse zone. For this reason reflections don't take place at the Conrad discontinuity and at the MOHO, which are preconditions for transversal quakes.

If, however, the focal depth is greater than the depth of the LVL (h ⩾ 10 km ±) the energy radiated from the focus slanting downwards to the north will be reflected by the discontinuities within the Bohemian Massif and so get up to Bohemia and farther, quite in the manner of transversal quakes (see fig. 6b). On the other hand, the energy radiated from the focus slanting upwards to the north gets into the LVL and reaches the surface in the Molasse zone and increases the local seismic intensity there. — With that the individual differences of earthquakes in the Semmering region are clarified, and our explanation of transversal quakes is fully confirmed.

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Abstrakt

Energie silných zemětřesení v sv. Alpách se šíří především k severu a severozápadu; přibližně eliptické oblasti otřesů jsou protaženy podél hlavních os probíhajících napříč k alpskému směru. Proto se taková-to zemětřesení od minulého století nazývají „příčná" neboli „transverzální". Anomální šíření energie alpských zemětřesení nebylo dosud uspokojivě vysvětleno žádným z autorů, kteří se o to pokusili. V této práci se nyní na základě výzkumů dokazuje, že anomální šíření energie transverzálních zemětřesení je důsledkem pouze zvláštní lokální topografie Mohorovičićovy diskontinuity, jakož i k J až JV strmě upadajících zlomových ploch uvnitř svrchní kůry. Hlavní část seizmické energie šířící se z ohniska zemětřesení šikmo dolů se v sz. kvadrantu zcela odráží od Conradovy a Mohorovičićovy diskontinuity, kdežto v jv. kvadrantu těmito rozhraními proniká. Tím lze tedy nyní rovněž bez jakýchkoliv pochyb vysvětlit nápadné rozdíly v šíření dvou zvláštních semmerinských zemětřesení.

Zusammenfassung

Die Energie starker Erdbeben in den nordöstlichen Alpen pflanzt sich bevorzugt nach Norden und Nordwesten fort; die näherungsweise elliptischen Schüttergebiete haben große Achsen, die transversal zum Streichen der Alpen verlaufen. Solche Beben werden daher seit dem vorigen Jahrhundert als „Transversalbeben" bezeichnet. Bis jetzt war noch kein Erklärungsversuch der anomalen Energieausbreitung befriedigend. In der vorliegenden Untersuchung wird nun nachgewiesen, daß die Ausbreitungsanomalie der Transversalbeben allein eine Folge der speziellen lokalen Topographie der Mohorovičić-Diskontinuität sowie der steil südbis südostwärts einfallenden Bruchflächen innerhalb der oberen Kruste ist: der Hauptanteil der vom Bebenherd schräg nach unten abgestrahlten seismischen Energie wird im Nordwestquadranten an der Conrad- und Mohorovičić-Diskontinuität total reflektiert, während sie im Südostquadranten diese Grenzflächen durchdringt. Es können nunmehr auffallende Unterschiede in der Ausbreitung von zwei speziellen Semmeringbeben ebenfalls zweifelsfrei erklärt werden.

COMPARISON OF THE FLYSCH ZONE OF THE EASTERN ALPS AND THE WESTERN CARPATHIANS BASED ON RECENT OBSERVATIONS

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1. Preface

Making comparisons between the Flysch Zone of the East Alps and the West Carpathians has a long-standing tradition, as earliest researchers investigated both sides