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A crustal cross section along the Swiss Geotraverse from the Rhinegraben to the Po Plain[1])

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ABSTRACT

The crustal cross section from the Rhinegraben to the Po Plain, i.e. along the Swiss Geotraverse, covers the geologic and tectonic units of the southern Rhinegraben, the Swiss folded Jura mountains, the Molasse basin, the Aar Massif, the Central or Penninic Alps between the Rhine-Rhone Line and the Insubric Line, and the Southern Alps. Intensive seismic refraction measurements were carried out in almost all of these units during the past 20 years. Thus a combined interpretation of all the available seismic refraction and a few deep reflection data allowed to construct a crustal cross section for this Geotraverse. The main results can be summarized in the following way:

1. The nowadays quiescent continental rift system of the Rhinegraben is characterized by a pronounced shallow mantle upwarp to a depth of only 25 km connected with a thick low-velocity zone in the upper crust.
2. This rift-type crustal structure is replaced further to the southeast in the folded Jura mountains and the adjacent Molasse basin by a "normal" continental type of crust as found under tectonically active areas. The crustal slab bounded by the top of the crystalline basement and the crust-mantle boundary has a constant thickness of 32 km dipping southeastward towards the northern margin of the Alps, where a total depth to the Moho of about 40 km is reached including the Molasse sediments. An upper crustal low-velocity layer and a second zone of reduced velocity in the transitional depth range above the crust-mantle boundary are typical for this crustal segment.
3. Further to the southeast apparently a crustal flake has been sheared off at the base of the upper crustal low-velocity zone and bent upward leading to the granitic core with gneissic envelopes of varying metamorphic grade which altogether compose the present-day Aar Massif.
4. The adjacent segment to the south comprising the Pennine Central Alps between the Rhine-Rhone Line and the Insubric Line is probably composed of two crustal blocks belonging originally to the Eurasian and African plate, respectively, with the northern lower crust extending at depth all the way to the Insubric Line. Both crustal segments may simply be superimposed on each other or intercalated in a complicated mode of layering which cannot be resolved from the presently available data. The main characteristics of this block are the low average *P* wave velocity of about 6 km/s with a thick low-velocity zone in the depth range of 26 to 44 km. The crust-mantle boundary reaches its greatest depth of 53 km under the southern half of the Pennine Alps, i.e. south of the central axis of the Alps, which clearly substantiates the asymmetric morphology of this boundary under the Alps.
5. Further to the south crossing the Insubric Line the crust-mantle boundary rises to a depth of 35 km under the Southern Alps. Velocities of 6.3 km/s in this relatively undisturbed crustal segment corroborate the hypothesis that it still reflects the features of a "rift flank"-type of crust which presumably developed in Lower Cretaceous time.

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ZUSAMMENFASSUNG

Der Krustenschnitt vom Rheingraben zur Po-Ebene entlang der Schweizer Geotraverse umfasst die geologischen und tektonischen Einheiten des südlichen Rheingrabens, des schweizerischen Faltenjura, des Molassebeckens, des Aar-Massivs, der Zentral- oder Penninischen Alpen zwischen der Rhein-Rhone-Linie und der Insubrischen Linie und der Südalpen. In nahezu all diesen Gebieten wurden in den zurückliegenden 20 Jahren umfangreiche refraktionsseismische Messungen durchgeführt, die zusammen mit einigen Steilwinkelreflexionen die Grundlage für den vorliegenden Krustenschnitt bilden. Die wesentlichsten Ergebnisse lassen sich folgendermassen zusammenfassen:

1. Das heute weitgehend zur Ruhe gekommene kontinentale Riftsystem des Rheingrabens ist gekennzeichnet durch eine ausgeprägte Zone erniedrigter Geschwindigkeit in der oberen Kruste und eine Aufwölbung der Krusten-Mantel-Grenze auf 25 km Tiefe.
2. Nach Südosten fortschreitend geht die Kruste unter dem Faltenjura und dem Molassebecken bis zum Alpennordrand über in den für unter Kontinenten charakteristischen Krustentyp mit einer Zone geringerer Geschwindigkeit in der Oberkruste und einer weiteren Geschwindigkeitsinversion im Übergangsbereich zur Moho. Das Krustensegment zwischen Kristallinoberfläche und Krusten-Mantel-Grenze senkt sich mit einer konstanten Mächtigkeit von 32 km nach Südosten zum Alpennordrand hin ab. Einschliesslich der Molassesedimente wird dort eine Moho-Tiefe von etwa 40 km erreicht.
3. Die seismischen Daten deuten an, dass im Aar-Massiv ein Krustenspan im unteren Bereich der Zone geringerer Geschwindigkeit abgeschert und nach oben gebogen worden ist. Der an der Oberfläche des Aar-Massivs anstehende granitische Kern und die ihn umgebenden Gneishüllen mit unterschiedlichem Metamorphosegrad bestätigen diese Hypothese.
4. Der südöstlich anschliessende Block des Penninikums zwischen Rhein-Rhone-Linie und Insubrischer Linie besteht vermutlich aus zwei übereinanderliegenden oder ineinandergeschobenen Krustenteilen, die ursprünglich der eurasischen und afrikanischen Platte zuzurechnen waren. Die untere Kruste der Nordalpen erstreckt sich vermutlich unter dem Aar-Massiv und dem Penninikum bis zur Insubrischen Linie hin. Die Kruste ist in diesem Gebiet vor allem durch die geringe mittlere Krustengeschwindigkeit von 6 km/s und eine ausgeprägte Zone verringerter Geschwindigkeit in der unteren Kruste zwischen 26 km und 44 km Tiefe gekennzeichnet. Unter dem Südrand des Penninikums, d.h. südlich der Alpenachse, erreicht die Krustenmächtigkeit ihren maximalen Wert von 53 km.
5. Beim Übergang zu den Südalpen jenseits der Insubrischen Linie steigt die Krusten-Mantel-Grenze relativ steil auf 35 km Tiefe an. Erhöhte Krustendurchschnittsgeschwindigkeiten von 6,3 km/s bestätigen die Herkunft dieses verhältnismässig ungestörten Krustenabschnitts aus der Flankenstruktur eines ehemaligen Riftsystems, das sich vermutlich in der Unteren Kreide entwickelte.

Introduction

Since 1956 a large amount of seismic refraction data, some deep reflection observations and extended results deduced from the dispersion of seismic surface waves have been collected throughout the region of the Alps. The areas of main interest have changed with time from the Zone of Ivrea in the Western Alps to the Dolomites and the northern Calcareous units in the Eastern Alps and back to the Central Alps. Tectonic features like the Rhinegraben and the Molasse basin in the north and the Po Plain or the Adriatic promontory in the south are closely related to the evolution of the Alpine chain. In Switzerland during the International Geodynamics Project interdisciplinary research along the Swiss Geotraverse was aimed at a comprehensive investigation of the lithospheric structure from the Rhinegraben in the north across the Alps to the Po Plain in the south. The crustal cross section characterized by the distribution of seismic velocities with depth along the Geotraverse should help in the understanding of the tectonic evolution of this area. A considerable amount of new data has been obtained since the first report about the crustal structure along the Swiss Geotraverse as determined from seismic experiments (MUELLER et al. 1976). Consequently the mechanism proposed at that time for the Alpine crustal evolution also had to be revised.

Geologic setting and seismic data

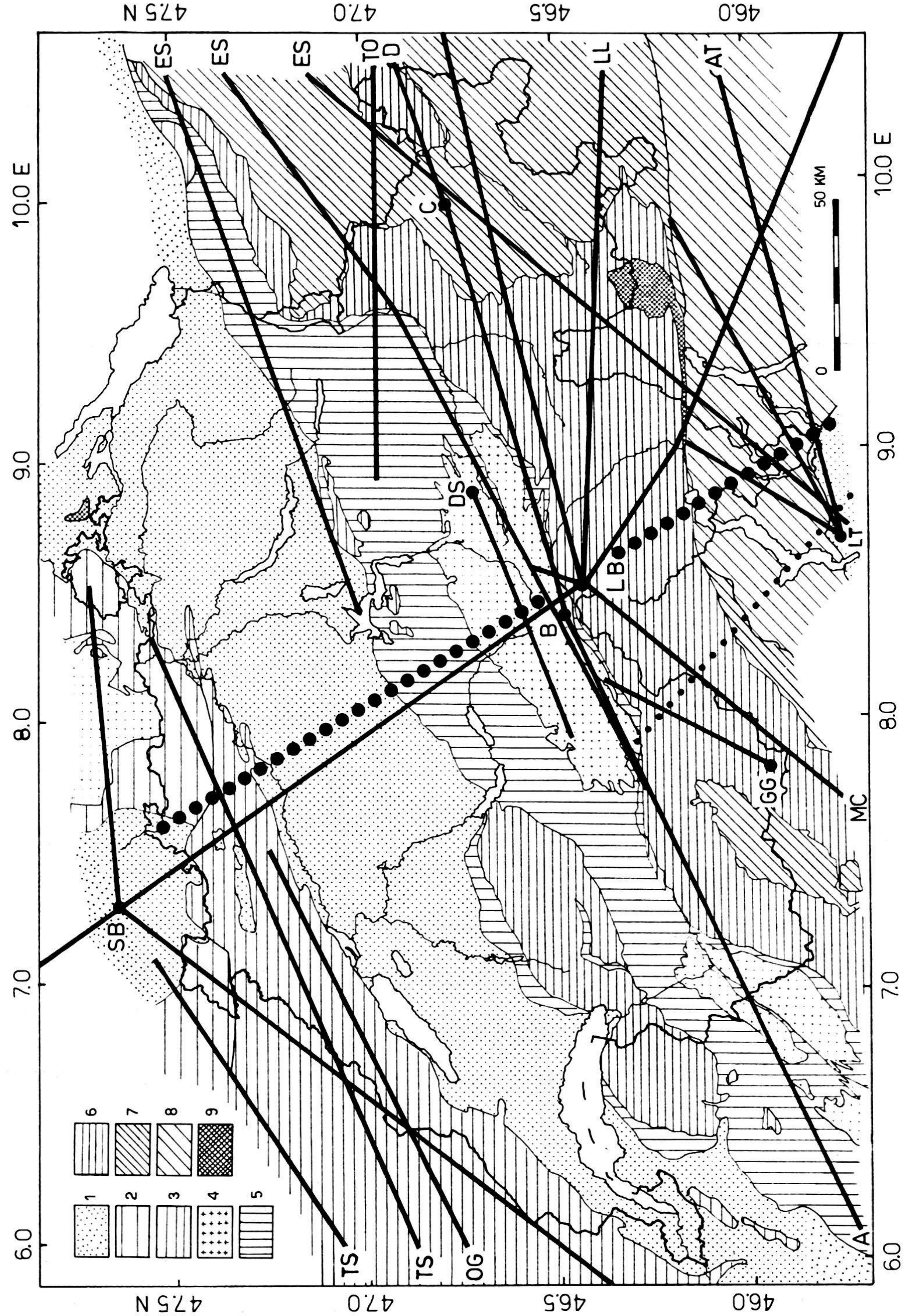
The Swiss Geotraverse cuts through the main tectonic and geologic units of Switzerland as shown by the large dotted line in Figure 1: It extends from the southern Rhinegraben near Basel across the folded Jura mountains through the Molasse basin, the Helvetic nappes, the Aar and Gotthard Massifs, the Austroalpine nappes of the Lepontine, and the Southern Alps to the Tertiary sediments of the Po Plain. Heavy dark lines in Figure 1 mark the geographic position of the various seismic refraction lines used for the determination of crustal structure in Switzerland for which the Geotraverse is intended to give a representative cross section. Shotpoints for the refraction measurements within the area of Figure 1 are indicated by full dots and letter codes. Lettering on the edges of Figure 1 denotes shotpoints outside the given frame. Technical details of the explosions and positions of the profiles as well as recording procedures and earlier interpretations have been published by CLOSS & LABROUSTE (1963), CHOUDHURY et al. (1971), GIESE & PRODEHL (1976), Alpine Explosion Seismology Group (1976) for the Western and Eastern Alps; by ANSORGE et al. (1979) for the Southern Alps; and by the Rhinegraben Research Group (1974) for the Rhinegraben area.

As can be seen in Figure 1 within Switzerland the Molasse basin, the Helvetic nappes and the Aar Massif are still poorly covered by refraction profiles, and hence the deduced crustal structure in these areas should be considered only as preliminary. The few data obtained from shotpoint *DS* in the Aar Massif (Fig. 1) indicate only that the crustal structure differs considerably from the areas to the north and south of this highly deformed unit.

In order to demonstrate the improved quality of the more recently obtained data from seismic refraction experiments which were already carried out as part of the Swiss Geotraverse project and to document the key data for the crustal structure derived, we have selected three record sections from the main tectonic units along the Geotraverse.

A much larger number of profiles of similar quality has, of course, been used in this study. Figures 2, 3 and 4 show the three seismogram assemblages. The absolute travel time (t) of each record trace is reduced by the quantity given as distance (Δ) divided by 6, i.e. a reduction velocity of 6 km/s has been used. The profiles selected are Steinbrunn–SW (shotpoint *SB*, Fig. 1) in the folded Jura mountains; the profile from the Nufenen-Pass eastward towards the Flüela-Pass in the Central or Penninic Alps (shotpoint *B* towards shotpoint *C* in Fig. 1); and in the Southern Alps a profile from the southern end of the Lago Maggiore to the east (shotpoint *LT* towards *AT* in Fig. 1).

The most pronounced phases common to all seismogram sections and those which demonstrate important lateral variations of the crustal structure are correlat-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ed on the record sections of Figures 2, 3 and 4. Rather significant differences in travel time and apparent velocity are obvious for the first arrivals near the shot-points, i.e. the sedimentary phases P_s. The influence of the laterally variable thickness of Quaternary sediments is clearly visible on the record section of the Southern Alps (Fig. 4). These sedimentary phases are followed in all three cases by the P_g phase which propagates through the crystalline basement with velocities between 6.0 and 6.1 km/s.

Another common feature on the three record sections are arrivals with a velocity between 6.1 and 6.3 km/s delayed by less than 1 s after the P_g phase. This phase is followed by a signal which has propagated with a velocity between 6.7 and 6.8 km/s under the Jura profile (Fig. 2) and the Central Alps (Fig. 3). No clear arrivals with this velocity can be traced along the profile in the Southern Alps which indicates probably a less differentiated crust in this area as compared to the profiles further north.

Strong later arrivals identified as the refracted (P_n) and overcritically reflected (P_MP) signals from the crust-mantle boundary follow the high-velocity intermediate phase of the northern profiles after a variable interval of travel time, i.e. approximately 1 s under the Jura mountains (Fig. 2) and 4-5 s under the Central Alps. This comparison should not be extrapolated to the Southern Alps, because in that area the high-velocity intermediate phase seems to be absent.

The two southern profiles show a few weak arrivals slightly before the P_MP and P_n phases which suggest relatively thin high-velocity layers (with P velocities of about 7 km/s) immediately above the crust-mantle boundary.

Interpretation

The inversion of the main travel time branches which have been shown in Figures 2, 3 and 4 and which are also observed on most of the other profiles in this area with the same consistent pattern (EGLOFF 1979) led to individual velocity-depth distributions for five of the main tectonic units along the Geotraverse (Fig. 5). The depth profiles for the Rhinegraben (solid line), the folded Jura mountains and the Helvetic zone of the Northern Alps show the same schematic velocity distribution. Pronounced differences mark the transition from the southern Rhinegraben rift system (MUELLER et al. 1973; PRODEHL et al. 1976) to the normal type of crust under the Jura mountains (EGLOFF & ANSORGE 1976). The thickness of the upper crustal

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Fig. 1. Shotpoint locations and positions of seismic refraction profiles on a schematic geologic-tectonic map of Switzerland.

1 = Tertiary Sediments, Molasse; 2 = Tabular Jura Mountains; 3 = folded Jura mountains; 4 = Crystalline Massifs and Basement, incl. Gotthard Massif; 5 = Helvetic Autochthonous Sediments, Helvetic and Ultrahelvetic nappes; 6 = Penninic nappes; 7 = Austroalpine nappes; 8 = Southern Alps; 9 = Tertiary Intrusives and Volcanics.

A, B, C, D = Shotpoints of the Alpine Longitudinal Profile (ALP 75); *AT* = Albiano/Trento; *DS* = Disentis; *ES* = Eschenlohe; *GG* = Gornergrat; *LB* = Lago Bianco; *LL* = Lago Lagorai; *LT* = Lentate/Varese; *MC* = Mt-Cenis; *OG* = Orgelet; *SB* = Steinbrunn; *TO* = Osttirol; *TS* = Tournus. ● = Location of Swiss Geotraverse; • = location of traverse Ivrea-Verbano.

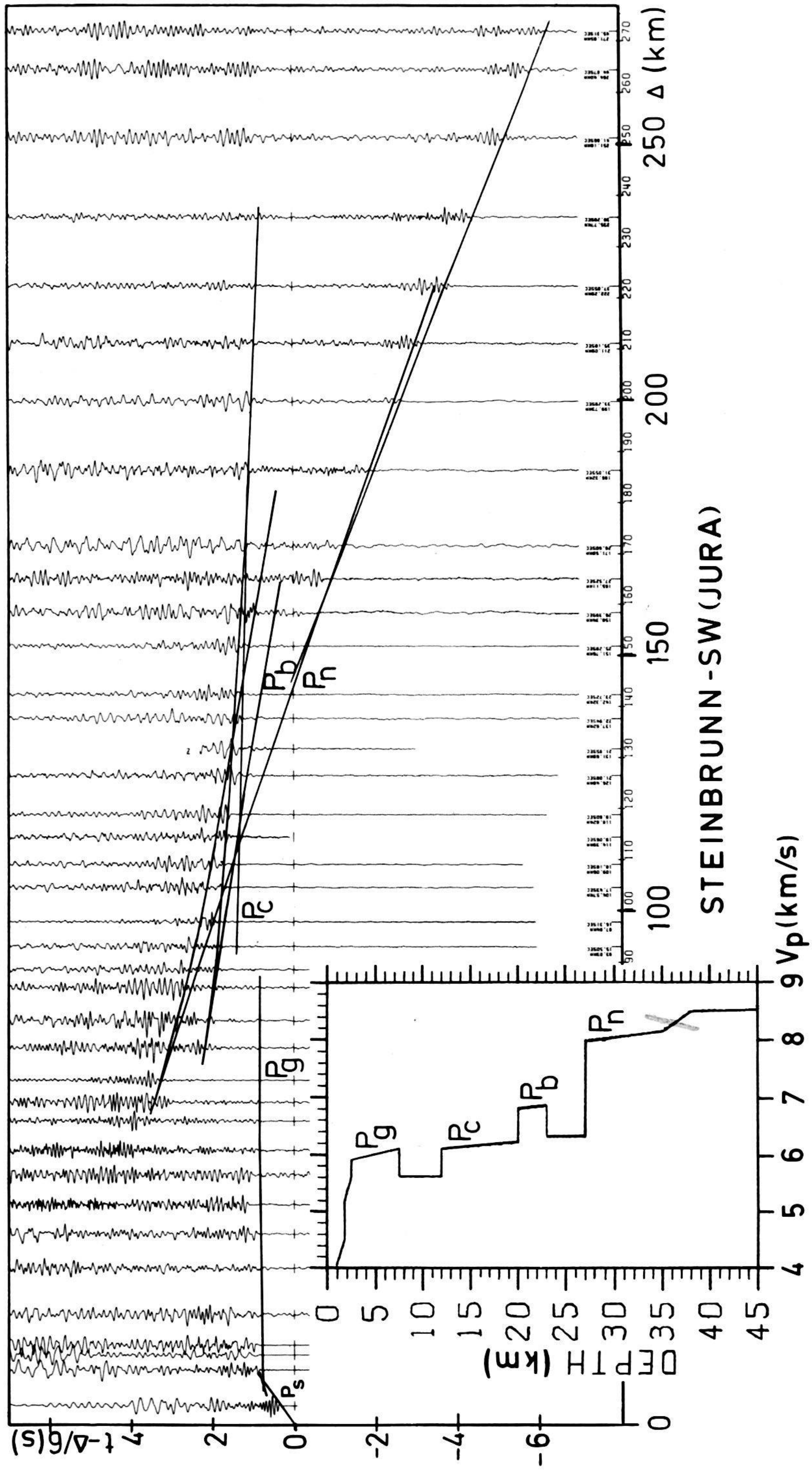


Fig. 2. Seismogram section for the Steinbrunn-SW profile following the strike of the folded Jura mountains. The signal correlations were calculated on the basis of the *P* velocity-depth functions shown in the inset (shotpoint *SB* in Fig. 1).

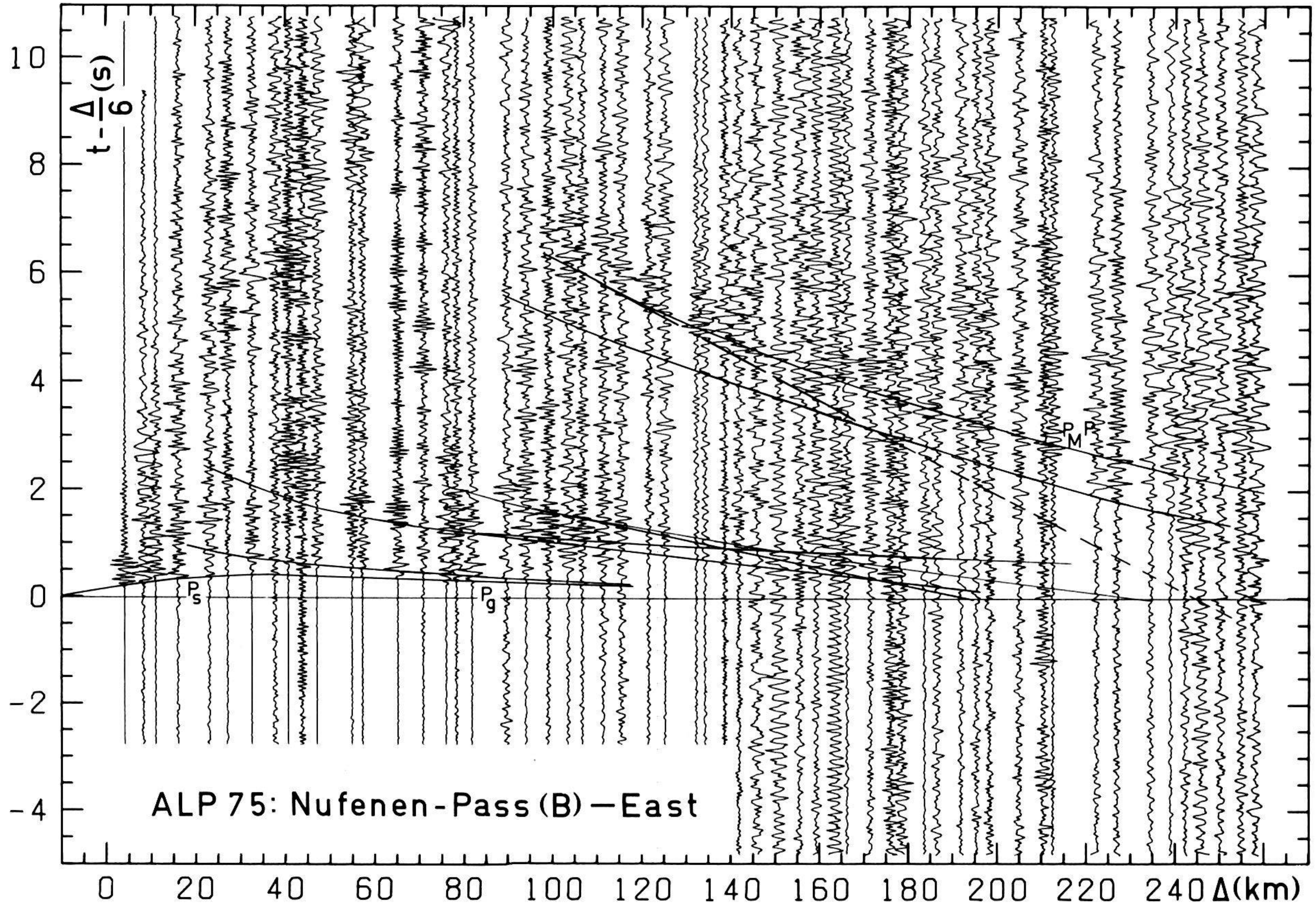


Fig. 3. Seismogram section for the profile Nufenen-Pass eastward towards the Flüela-Pass (shotpoint *B* towards shotpoint *C* in Fig. 1) through the Central Alps. Correlations were calculated based on the corresponding *P* velocity-depth function shown in Figure 5.

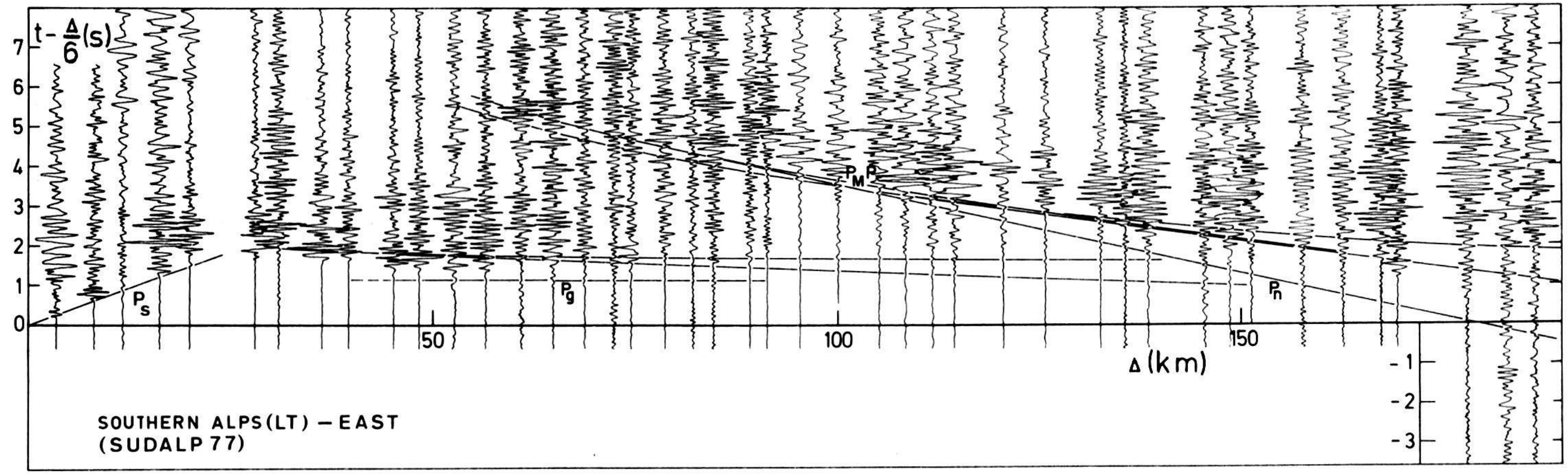


Fig. 4. Seismogram section for the profile near the southern end of the Lago Maggiore to the east (shotpoint *LT* towards shotpoint *AT* in Fig. 1). Correlations were calculated based on the corresponding *P* velocity-depth function shown in Figure 5.

low-velocity zone decreases markedly whereas the depth to the crust-mantle boundary shows a pronounced increase towards the northern margin of the Alps.

The model for the northern Helvetic zone was derived from the profile Eschenlohe-W terminating near Einsiedeln (northernmost profile from shotpoint Eschenlohe-ES in Fig. 1) and extrapolated along the Helvetic zone onto the Geotraverse. A thin shallow zone of low velocity (depth range 3.5 km to 6.5 km) characterizes this area. It is caused by the overthrust of the Helvetic nappes with higher velocities over the slower material of the folded Molasse basin. This type of interpretation had been suggested by WILL (1976) for the northern Calcareous Alps east of the shotpoint Eschenlohe. It has been confirmed recently by the results from detailed seismic reflection measurements in the course of exploration work for hydrocarbon deposits (BEB 1979) close to the Swiss Geotraverse (Fig. 9).

A low-velocity zone (velocity reduction of 3 to 10%) separates the upper crystalline basement with velocities of about 6 km/s from the middle crust under all three northern velocity-depth distributions (Fig. 5). A zone with velocities ranging from 6.1 to 6.3 km/s is interrupted by a relatively thin high-velocity zone with values around 7 km/s which effectively produces a second low-velocity layer immediately above the crust-mantle boundary. This general type of continental crust for tectonically active areas has been discussed in detail by MUELLER (1977). The depth to the crust-mantle boundary increases smoothly from 25 km under the southern Rhinegraben to slightly less than 40 km under the Helvetic zone of the Northern Alps.

In contrast to these first three models a very different crustal structure is found under the Pennine zone of the Central Alps (Fig. 5). Taking the high-velocity layer with P velocities of about 7 km/s in the lower crust of the northern foreland as a reference horizon two alternative correlations have to be discussed for the crustal structure under the Lepontine area. The high-velocity "tooth" at a depth of about 25 km must be considered to be characteristic of an original feature in the lower Alpine crust which has been uplifted by 20 to 25 km as indicated by the observed metamorphism of rocks exposed at the surface in that region (FREY et al. 1976). In

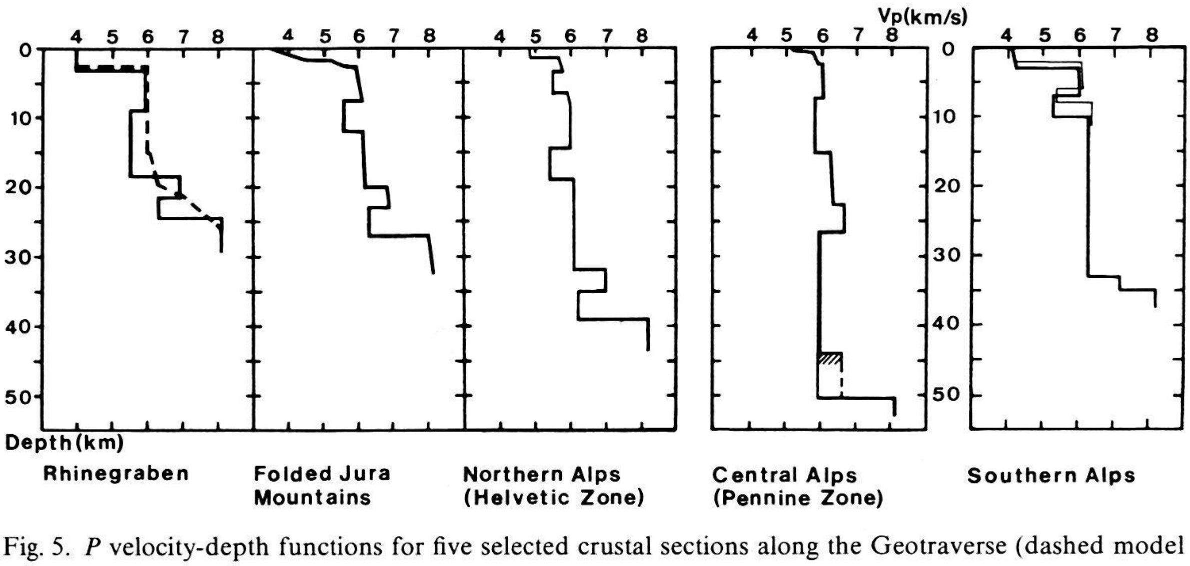


Fig. 5. P velocity-depth functions for five selected crustal sections along the Geotraverse (dashed model for the Rhinegraben after EDEL et al. 1975).

our view a correlation with the high-velocity step at a depth of 44 km under the Central Alps is the more likely answer. This interpretation implies that the lower crust of the northern foreland extends under the Pennine zone, but has been separated from its upper part by a relatively thick layer of a "uniform", little differentiated structure with an average *P* velocity of not more than 6 km/s ranging from a depth of 26 km down to 44 km. It cannot be resolved in more detail with the presently available data. The crust-mantle boundary in this section of the Geotraverse lies at a depth of 50 km.

The crustal structure changes again abruptly when reaching the Southern Alps as can be seen from the fifth model in Figure 5 (right-hand side). The crustal thickness decreases sharply from 54 km under the Central Alps to 35 km under the Southern Alps, which is much shallower than the value of 42 km derived by STEIN et al. (1978) for the same area. Except for the uppermost part of the crust no fine structure seems to exist within the crust. However, the average *P* velocity is slightly higher than that found in the northern foreland of the Alps. This structure with the thin high-velocity transition layer directly overlying the Moho is similar to what is normally found under rift flanks at an evolutionary stage shortly before the acute break-up of a continental plate sets in (MUELLER 1978). This structural feature would be in agreement with palinspastic reconstructions postulating a tensional phase in Lower Cretaceous time (BÜCHI & TRÜMPY 1976) which must have led to extensive rifting.

The dense coverage of Switzerland and its adjacent areas with seismic refraction profiles (Fig. 1) has permitted us to compile a contour map of the crust-mantle boundary as shown in Figure 6. A recently completed Moho map of Switzerland (EGLOFF 1979) was combined with the results from the Rhinegraben (EDEL et al. 1975), the Bresse-Graben (MICHEL 1978), southern Germany (EMTER 1971; GIESE 1976), and from the Eastern Alps (MILLER et al. 1977). Additional data incorporated in this map were taken from the Alpine Explosion Seismology Group (1976), MILLER et al. (1978); and ANSORGE et al. (1979).

As mentioned before some features of the crustal structure were extrapolated or projected onto the Swiss Geotraverse. The contour map of the Moho in Figure 6 justifies this procedure within certain limits, and the proposed crustal structure under the Geotraverse can be considered as representative for the area under discussion.

The Swiss Geotraverse connects the diapiric mantle upwarp under the southern Rhinegraben with the Po Plain across the area where the highest lateral compression occurred throughout the evolution of the Alps. All the external contour lines of the Moho are squeezed together both from the northwest and southeast towards the center of the Alps.

The depth of the Moho along the Geotraverse exhibits an asymmetric shape with respect to the main axis of the Alps in agreement with the interpretation of gravity and earlier seismic data by KAHLE et al. (1976*a*, *b*). A more gentle decrease from 25 km near the southern end of the Rhinegraben to about 54 km under the Lepontine area contrasts to a rather steep rise to 35 km under the Southern Alps.

The mantle upwarp under the Rhinegraben extends most probably southwestward to the Bresse-Graben north of Lyon (Fig. 6) and eventually further west to the

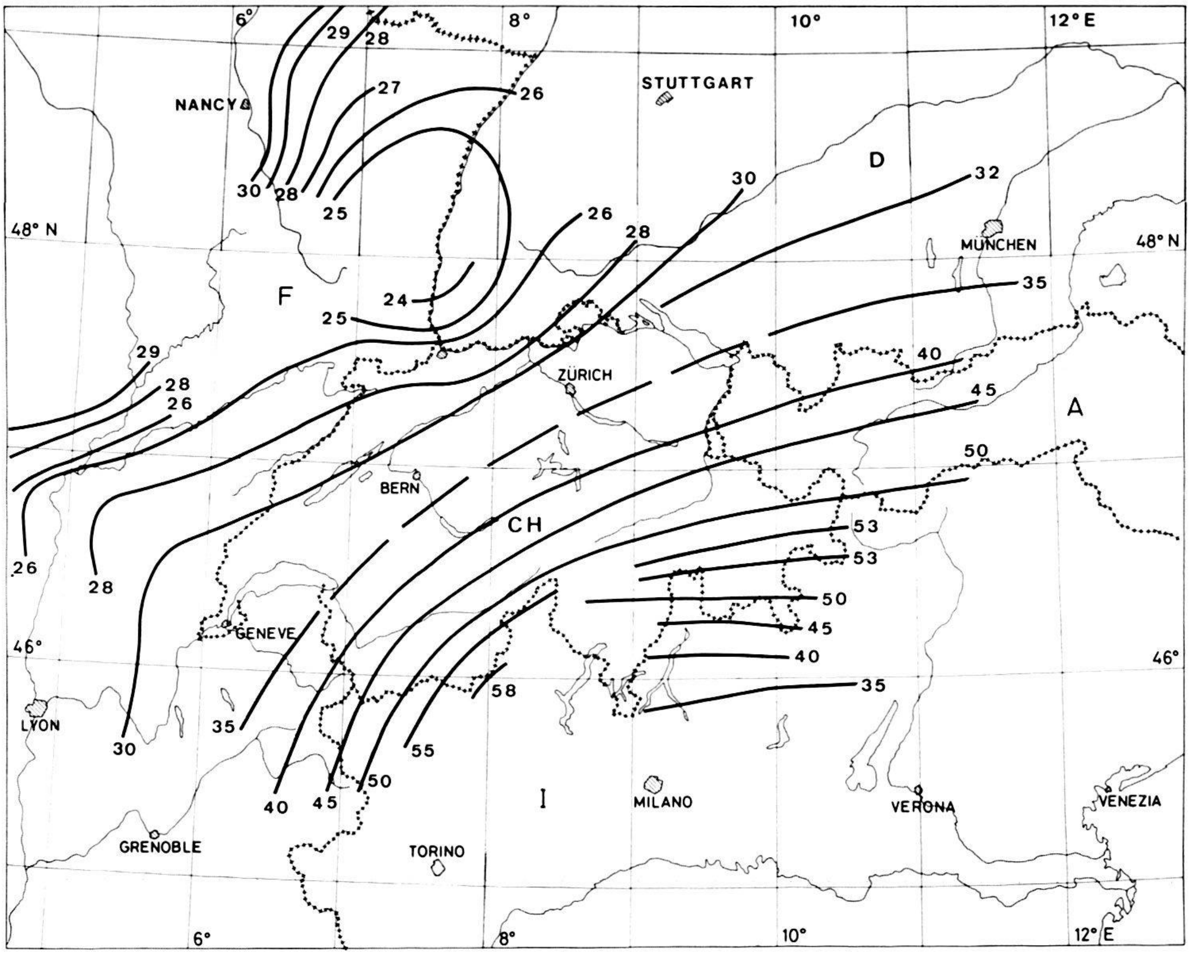
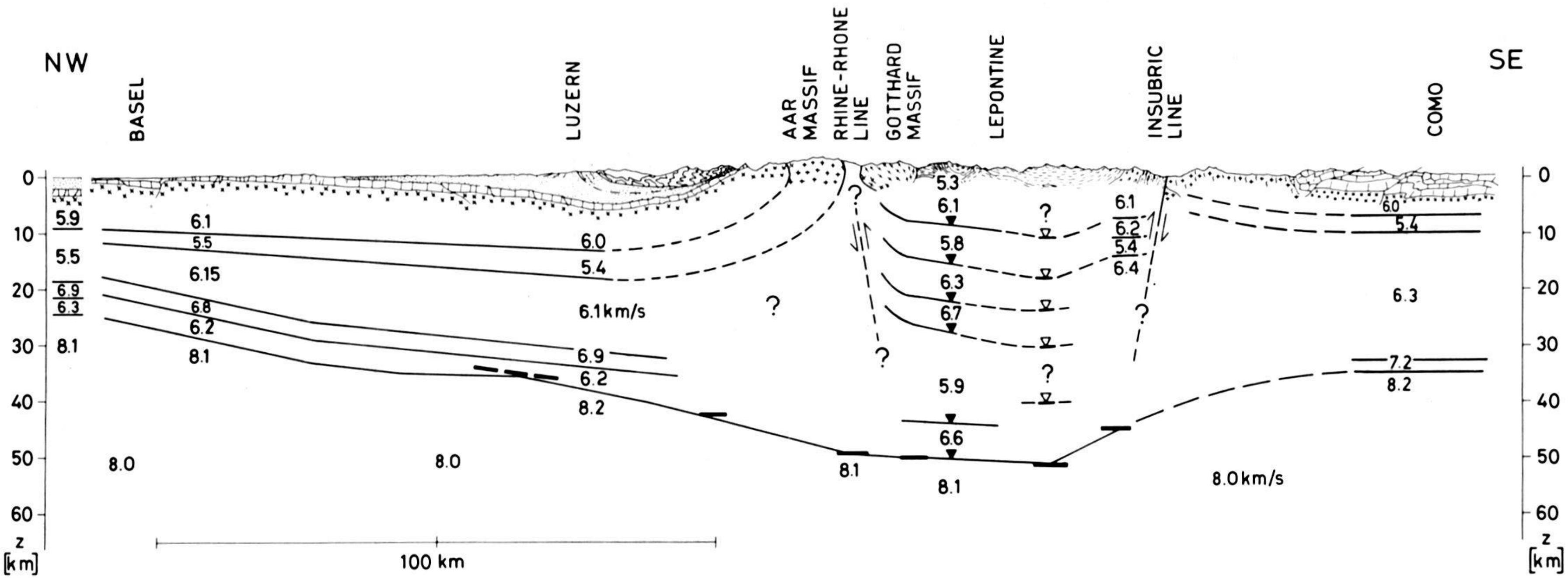


Fig. 6. Depth contours of the crust-mantle boundary in Switzerland and the surrounding areas after EGLOFF (1979), and Alpine Explosion Seismology Group (1976), ANSORGE et al. (1979), EDEL et al. (1975), EMTER (1971), GIESE (1976), MILLER et al. (1977, 1978).

Central Massif of France as shown by MICHEL (1978). The crustal structure of the Zone of Ivrea on the inner arc of the Alps northwest of Torino (Fig. 6) will be discussed briefly at the end of this paper and has been omitted in Figure 6, because it is not directly related to the Geotraverse.

Crustal cross section

In Figure 7 we have tried to construct a representative crustal cross section by combining all available refraction seismic data along the Swiss Geotraverse. Starting in the northwest close to the pronounced mantle upwarp under the southern Rhinegraben the entire crust dips down towards the southeast beneath the increasing sedimentary cover of the Molasse basin. Only minor internal variations of velocities and thicknesses of the crustal layers seem to occur with the Moho running more or less parallel to the boundary between the Mesozoic formations and the crystalline basement. Heavy bars in Figure 7 indicate the depth of the crust-mantle boundary as it has been determined from the evaluation of wide-angle reflections by the t^2, x^2 method.



▬ = Depth of the crust-mantle boundary after EGLOFF (1979).
▼ = Depth derived from near-vertical reflections after WEHEBRINK (1968).

Fig. 7. Proposed crustal cross section along the Swiss Geotraverse according to geological and geophysical data (Geology after BÜCHI & TRÜMPY 1976).

The upper crustal low-velocity layer which seems to exist throughout the northern segment of the Geotraverse is well documented also by additional observations from shotpoint Steinbrunn (*SB* in Fig. 1) towards the east as shown on the record section of Figure 8. The P_g branch which is recorded over the entire observation range of 90 km is followed by the near-vertical and wide-angle reflections from the top of the low-velocity zone indicating a rather abrupt decrease of the velocity at that boundary. Wide-angle reflections from the bottom of the low-velocity layer were recorded about 0.7 s later than those from the upper boundary. The relative amplitudes of P_g and later following phases reflected from the low-velocity layer are crucially influenced by the velocity gradients in each layer and across the interfaces of the various layers (EGLOFF 1979).

The following segment of the Geotraverse to the southeast, i.e. the crustal structure under the Aar Massif, seems to be rather complicated and is not yet completely understood. This is partly due to the lack of sufficient information from deep seismic experiments in this area. The relatively low P_g velocities which were observed along the short profile through the Aar Massif (shotpoint *DS* in Fig. 1) (OTTINGER 1976) and the surface geology with the granitic complex in the axial center of the massif (see Fig. 11) suggests that in this area the upper crust has been sheared off at the base of the low-velocity zone. The lateral intrusion of crustal material from the southeast has bent these layers upwards in a flake-type manner as indicated in Figure 7 (LAUBSCHER 1970; OXBURGH 1972). The observed backward

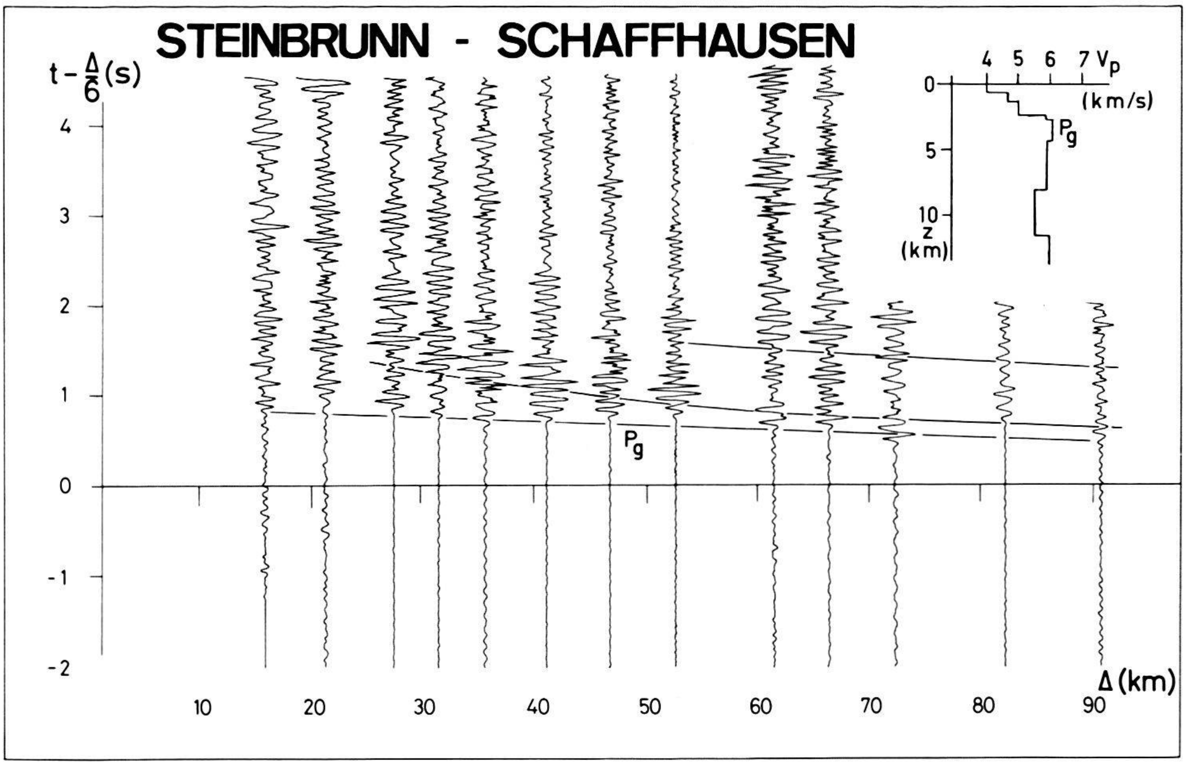


Fig. 8. Seismogram section for the profile Steinbrunn–Schaffhausen (extending from shotpoint *SB* in Fig. 1 to the east). Correlations were calculated based on the *P* velocity-depth function shown in the inset which illustrates the existence of a low-velocity layer in the upper crust.

thrust of the geologic units may be restricted only to the surface on top of a relatively homogeneous upper crust without pronounced velocity variations down to a depth of at least 15 km under the central part of the Aar Massif according to the observations from shotpoint *DS* (EGLOFF 1979). The grade of metamorphism observed in that part of the Alps (FREY et al. 1976) suggests that the material of the exposed Aar Massif has once resided at depths of about 10 to 12 km. If the crustal flake in Figure 7 is bent back into its original position it would fall into the appropriate depth range.

The geologic cross section in the uppermost part of Figure 7 was taken from BÜCHI and TRÜMPY (1976). Recently published data from seismic reflection mea-

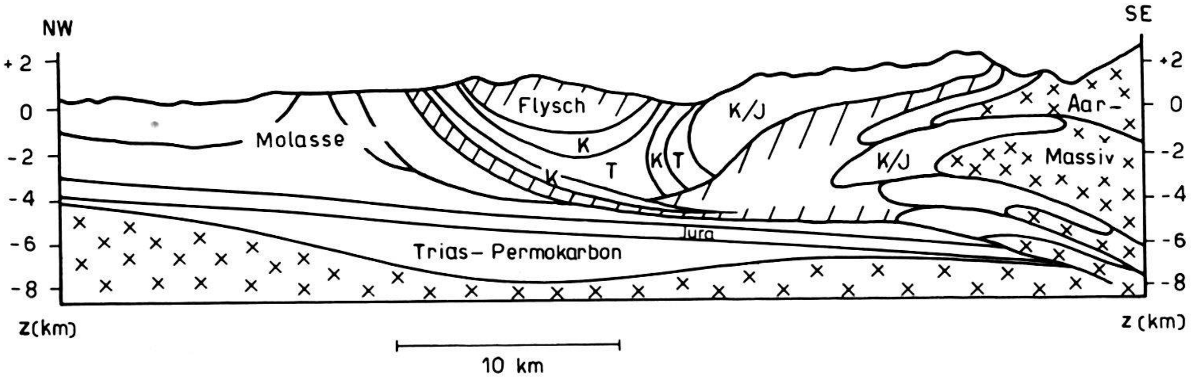


Fig. 9. Schematic geologic structure along the Swiss Geotraverse near the northern margin of the Alps obtained from seismic reflection work after BEB (1979). The section reaches from about 20 km west of Luzern to the northern margin of the Aar Massif.

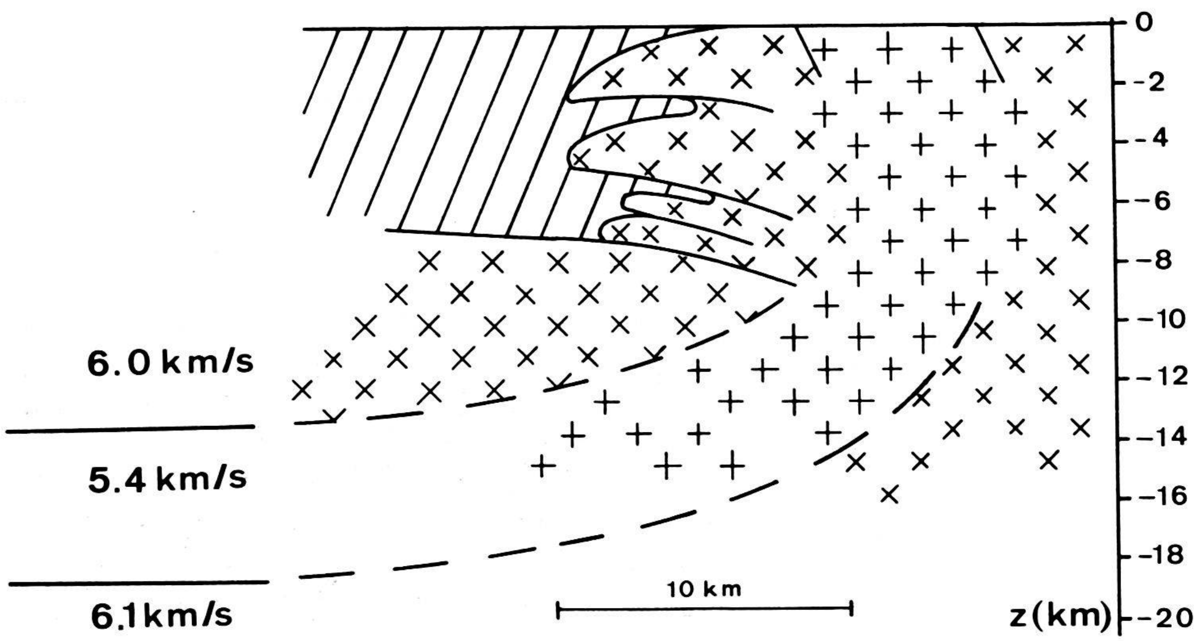


Fig. 10. Sketch combining the near-surface structure as shown in Figure 9 and the upper crustal structure as derived from refraction seismic observations near the northern margin of the Aar Massif. A low-velocity granitic core is bent upwards covered by gneissic material to the north and south of it.

surements (BEB 1979) show a much more complicated structure of the Mesozoic and Tertiary sediments and their interaction with the northern boundary of the Aar Massif than has been assumed so far. This new model is shown schematically in Figure 9 where the outer part of the Aar Massif, i.e. the gneissic envelope of the granitic intrusive masses has been thrust over the Mesozoic sediments with alternate intercalations reaching to a depth of about 8 km. However, these new data do not imply that the boundary between the sediments and the crystalline basement is the main shearing horizon along which the Aar Massif has been pushed upwards to the northeast over a distance of several hundred kilometers as suggested recently by Hsü (1979). As shown above the central granitic part of the Aar Massif is most probably derived from the laccolithic zone of granitic intrusions which compose the sialic low-velocity zone in the upper crust of tectonically active areas (Mueller 1977) and which has been pushed upwards in a flake-type manner. An example of the present-day situation is shown in Figure 11 where the light grey granitic Bietschhorn in the central Aar Massif surmounts the dark grey outer envelope to the southeast, which is composed of dark gneissic material.

The sketch in Figure 10 incorporates the newly obtained data from the reflection measurements as well as the deep seismic refraction observations near the northern boundary of the Aar Massif. The already earlier proposed model for the development of the Aar Massif (Mueller et al. 1976), i.e. the uplift of an upper crustal flake sheared off at the base of a low-velocity zone, is compatible with the upper basement structure derived from reflection measurements (Fig. 9). The actual relative position of gneissic and granitic parts in the Aar Massif varies from the sequence shown in Figure 11 to alternate vertical sequences (Fig. 10) and in some places even to granitic portions thrust over gneissic ones with strong lateral variations. The steeply dipping northern boundary of the crystalline basement is also demonstrated

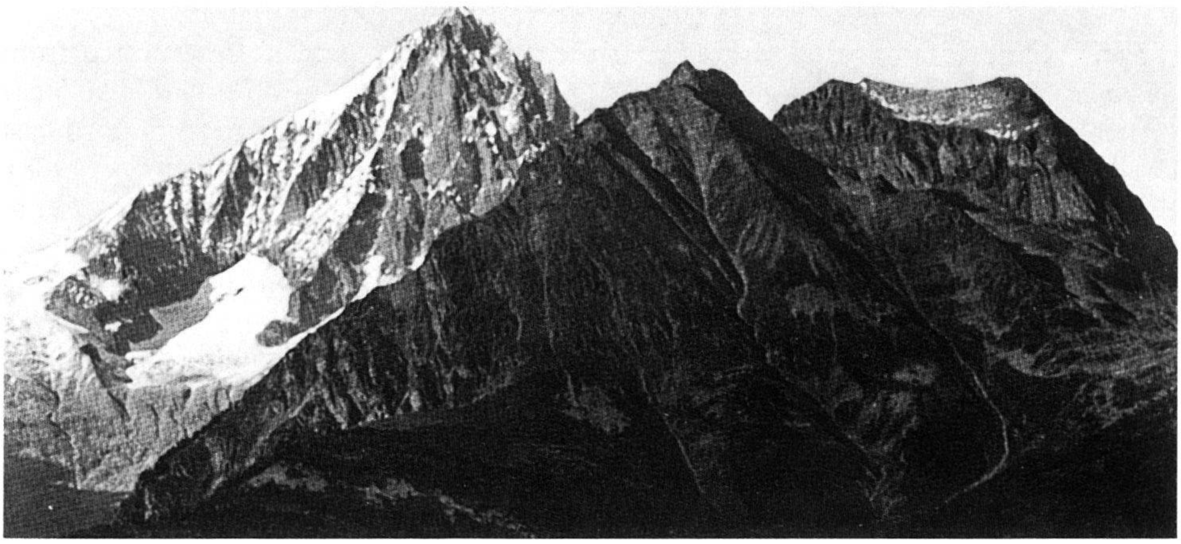


Fig. 11. The granitic Bietschhorn (3934 m) – light grey color – in the central Aar Massif as seen from the south across the Rhine–Rhone Line. In front of it lies the dark gneissic envelope immediately north of the Rhone valley.

by the focal mechanism of regional earthquakes which show a clear component of thrust displacement (AHORNER et al. 1972).

A high-velocity layer of 6.7 km/s is normally found in the lower crust or in transition zones at the bottom of the crust, as for instance under the folded Jura mountains or in the Eastern Alps (MILLER et al. 1977). As mentioned earlier in the Penninic or Central Alpine section of the Geotraverse this characteristic high velocity is found both at an intermediate depth followed by a pronounced layer of low velocity and in a normal type of transition (6.6–6.7 km/s) to the Moho (Fig. 5 and 7). This sequence of velocities can be interpreted by the extension of the northern lower crust reaching southward approximately to the Insubric Line (Fig. 7) overlain by a different crustal block with its northern boundary near the Rhine-Rhone Line. The top of the low-velocity zone (i.e. the depth of approximately 26 to 30 km) in the present-day lower crust of this area would then be the horizon permitting the relative motion of these two crustal blocks. It is very probable that both processes, uplift and northwestward translation, occurred at the same time over a long distance. However, the amount of translation and geologic history cannot be determined from the presently available seismic data.

This has some important implications for the Rhine-Rhone Line and the Insubric Line. The slope of the Rhine-Rhone Line as shown in Figure 7 may be too steep or not as deep-reaching because the crustal structure is known very close to this fracture zone. The Insubric Line must be considerably younger than the still ongoing uplift of the Lepontine block otherwise the zone of relative vertical motion would not be restricted to such a sharp boundary. Repeated first-order levelling along the Geotraverse has demonstrated a still continuing recent crustal uplift of considerable extent which has its maximum in the Lepontine area bounded by the Rhine-Rhone Line and the Insubric Line (JEANRICHARD 1972, 1975; GUBLER 1976). The rather steep rise of the crust-mantle boundary near the southern boundary of the Lepontine (Fig. 7) towards the south coincides with the position of the Insubric Line which may be another indication that this is a rather deep-reaching fracture zone as already suggested by GANSSER (1968) and LAUBSCHER (1970, 1977).

The complicated crustal structure of the Lepontine region as determined from seismic refraction observations seems to be supported by the observation of near vertical seismic reflections which were obtained in an azimuth range from northeast to southeast from the explosions in the Lago Bianco 1964 (WEHEBRINK 1968). Figure 12 shows an example of the reflections observed to the northeast (see inset in Fig. 12) which are marked according to their character and quality. Black triangles indicate the two-way travel times calculated for the intracrustal interfaces of the model shown in Figures 5 and 7. The strongly differentiated upper crust is very well confirmed. In addition reflections of minor quality suggest a less pronounced differentiation in the lower crust which is characterized by a low average velocity of 5.9 to 6.0 km/s as derived from seismic refraction observations.

The Southern Alps south of the Insubric Line seem to consist of a relatively undisturbed stable crustal block of continental ("rift flank") type with little structural variations except for a minor zone of low velocity in the upper crust and a thin transition layer above the Moho (ANSORGE et al. 1979). The rather abrupt change of the crustal structure across the Insubric Line may be explained by a model proposed

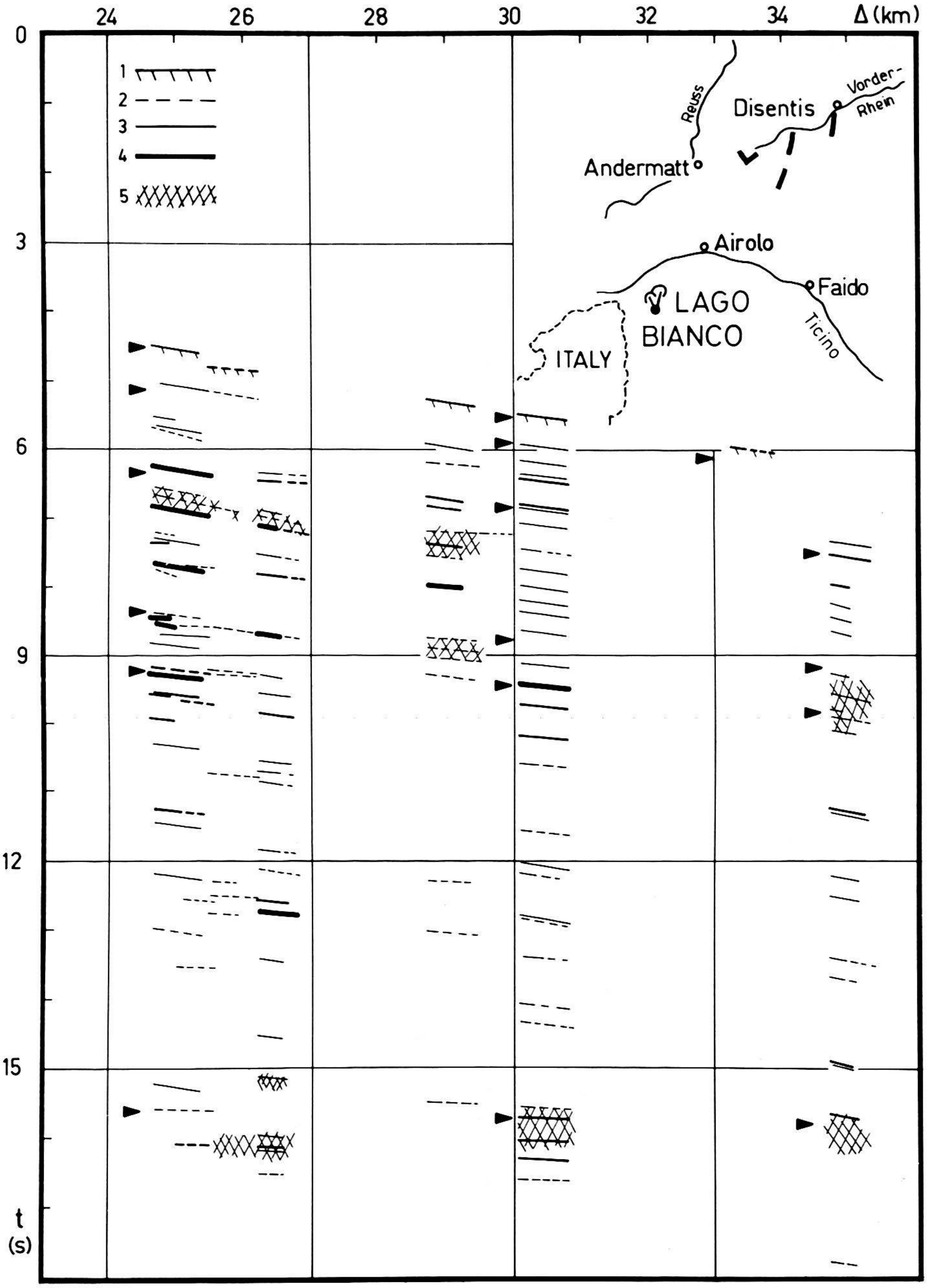
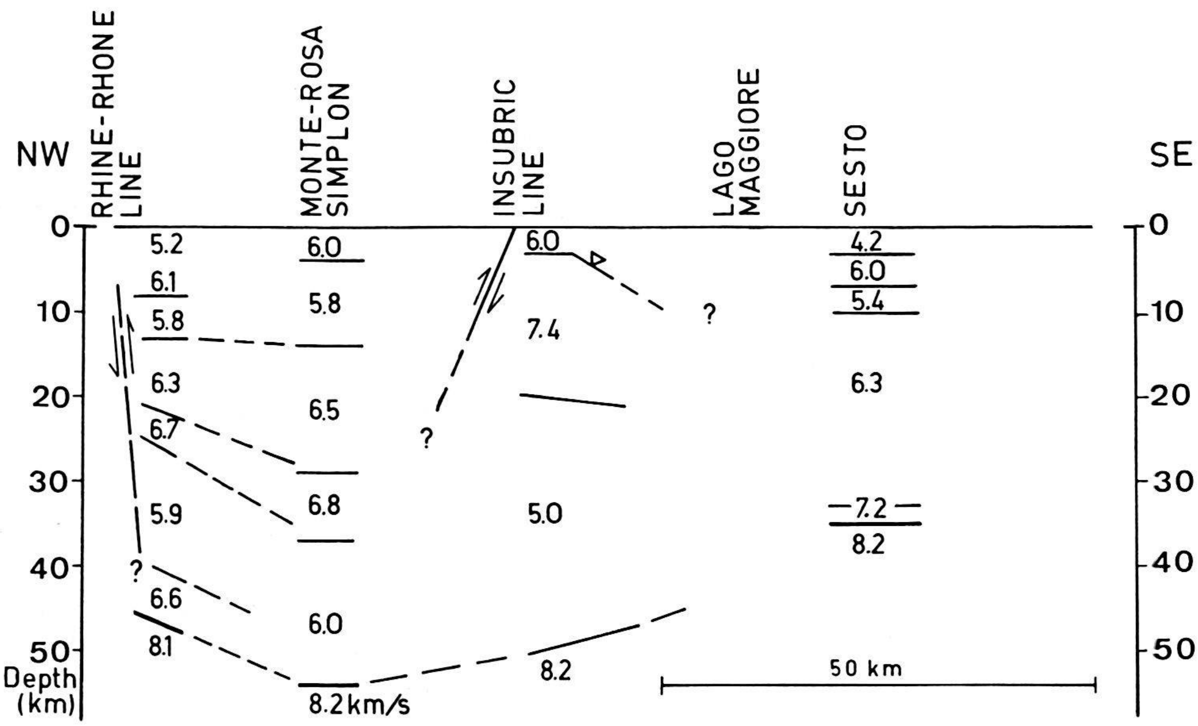


Fig. 12. Comparison of two-way travel times from near-vertical deep reflection observations northeast of shotpoint Lago Bianco after WEHEBRINK (1968) with travel times calculated from the refraction-seismic model for the Central Alps in Figure 5 (indicated by black triangles). The location of the reflection spreads is marked by heavy bars in the inset. 1 = First arrivals, 2 = week reflections, 3 = normal reflections, 4 = good reflections, 5 = reflection bands.

by LAUBSCHER (1977). According to LAUBSCHER this fault system represents the surface trace along which a steeply descending slab was broken off at a northward dipping subduction zone leaving behind the undisturbed continental block of the Southern Alps. The continuing movement of the southern Alpine block would then lead to an uplift of the Central Alpine block as observed from repeated first-order levelling (GUBLER et al. 1980). It would also cause a continuous downward motion of portions of the lithosphere. The resulting zone of extension might be sought in the lower Alpine crust where we observe the lower *P*-wave velocities.

Supplementary cross section through the Zone of Ivrea

In the final section we want to compare the crustal structure along the Swiss Geotraverse, i.e. across the Central Alps and Southern Alps, with a more schematic cross section further to the southwest from the Rhine–Rhone Line across the Zone of Ivrea–Verbano (Fig. 13). The structure near the Rhine–Rhone Line shown in Figure 7 has been extrapolated along this fracture zone to the southwest. The proposed velocity-depth model can easily be compared with the structure under the Monte Rosa and Simplon area as derived by ANSORGE (1968) from the profile Lago Bianco–Mt-Cenis (Fig. 1). KISSLING et al. (1978) conclude from a detailed gravity survey along the same traverse that the Insubric Line dips steeply towards the northwest down to a depth of at least 12 km and coincides with the northwestern boundary of the high-velocity/high-density Ivrea body (German Research Group



▽ = Reflections obtained from the shotpoint Monte Bavarione in 1960 (RICHARD 1963).

Fig. 13. Crustal cross section extending from the Rhine–Rhone Line near Brig (Valais) across the Zone of Ivrea to the eastern shore of Lago Maggiore in the Southern Alps.

For Explosion Seismology 1968). A rather strong lateral variation of the crustal structure has to be postulated also to the southeast of the Zone of Ivrea in order to blend into the more or less undisturbed crustal structure of the Southern Alps east of the Lago Maggiore (shotpoint *LT*, Fig. 1). The eastward dip of the Ivrea body has been determined from the observation of seismic reflections near the shotpoint Monte Bavarione in 1960 which were compiled by RICHARD (1963). Deep reflection measurements near the shotpoint Lentate (Fig. 1) confirm the crustal thickness in this area as determined from seismic refraction measurements.

Summary

Through a unified interpretation of all available seismic refraction profiles and a few deep-reflection observations in Switzerland it has been possible to construct a crustal section along the Swiss Geotraverse from Basel to Chiasso/Como. Most of the profiles are aligned along the strike of the major tectonic units thus permitting a penetration deep enough to deduce a representative *P* velocity-depth function for that region.

The detailed crustal section obtained exhibits an asymmetric crust-mantle boundary which dips down towards the southeast from a shallow mantle upwarp of less than 25 km depth under the southern Rhinegraben to a depth of about 40 km under the northern margin of the Alps and of about 50 km under the Central Alps. The segment Basel-Luzern of the Geotraverse is characterized by a "normal" continental crust as found in tectonically active areas with an upper crustal low-velocity layer and a second zone of reduced velocity in the transitional depth range just above the base of the crust.

Under the Aar Massif bordering the Rhine-Rhone Line in the south this type of crust seems to have been strongly affected by the Alpine orogeny. There an upper crustal flake has apparently been sheared off close to the base of the upper low-velocity zone and then has been bent upward. It is now visible at the surface as the central granitic core of the Aar Massif embedded in gneissic envelopes to the north and south. The observed grade of metamorphism suggests that this material has once resided at depths of about 10 to 12 km.

The lower crust of the northern foreland probably extends all the way under the Penninic block of the Lepontine Alps. Whether in this region two separate crustal slabs are superimposed on each other or a stack of several crustal slices is pushed into each other like a deck of cards cannot yet be decided. This complicated crustal structure characterized by a low average velocity under the Central Alps is supported by the highly metamorphosed units found at the surface which must have been uplifted by 20 to 25 km.

South of the Insubric Line the crust-mantle boundary is found at a depth of about 35 km under the Southern Alps. The higher average crustal velocity in that region strongly indicates that the crust has preserved its characteristic features as a structure of the "rift flank" type which must have been affected by extensive rifting in Lower Cretaceous time.

It is, of course, clear that the complex crustal structure presented in this paper is only the "near-surface" expression of a much deeper-reaching disturbance caused

by the collision of the Eurasian plate with the Adriatic promontory of the African plate. There is evidence that the entire lithosphere-asthenosphere system is affected by this process and there are indications that the collision front may extend to even greater depths, i.e. well into the mantle transition zone.

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