Pageoph, Vol. 114 (1976), Birkhäuser Verlag, Basel

A Lithospheric Seismic Profile along the Axis of the Alps, 1975
I: First Results

Alpine Explosion Seismology Group[1])

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Summary – From 8 to 20 September 1975 refraction seismic measurements were carried out in close European cooperation on a long range profile along the strike of the Alps between France and Hungary. The execution and first results of the Alpine Longitudinal Profile 1975 are presented in this paper, which is the first of a series. 20 shots from 9 different shotpoints were recorded by 193 mobile stations along a main line of a length of 850 km as well as on a number of fans and additional shorter profiles. The recordings were subsequently digitized and a number of computer generated record sections are presented to illustrate the quality of the data. First results are given in the form of a simple crustal cross section along the main profile and of two velocity depth functions, which indicate a substantial difference in type between the westernmost part and the eastern part of the profile.

1. Introduction

One may safely state that the Alps are the one mountain system on earth which has been investigated most extensively by geological and geophysical methods. To unravel the mysteries of mountain building generations of geologists and geophysicists have worked together employing all possible methods.

Since the early fifties joint refraction seismic studies have been carried out along a large number of profiles by many research teams from the European countries within and surrounding the Alps. These investigations were performed as joint ventures under the auspices of the European Seismological Commission, which, following a proposal by W. Hiller, established a subcommission for Alpine Explosions in 1954. As more and more data were gathered over the years from a great number of shotpoints a network of refraction seismic profiles covered the Alps. Figure 1 shows all profiles observed up to 1974. Results from these investigations have been published extensively including several review articles where the data are not only compiled but also interpreted homogeneously (Closs and Labrouste, 1963; Choudhury,

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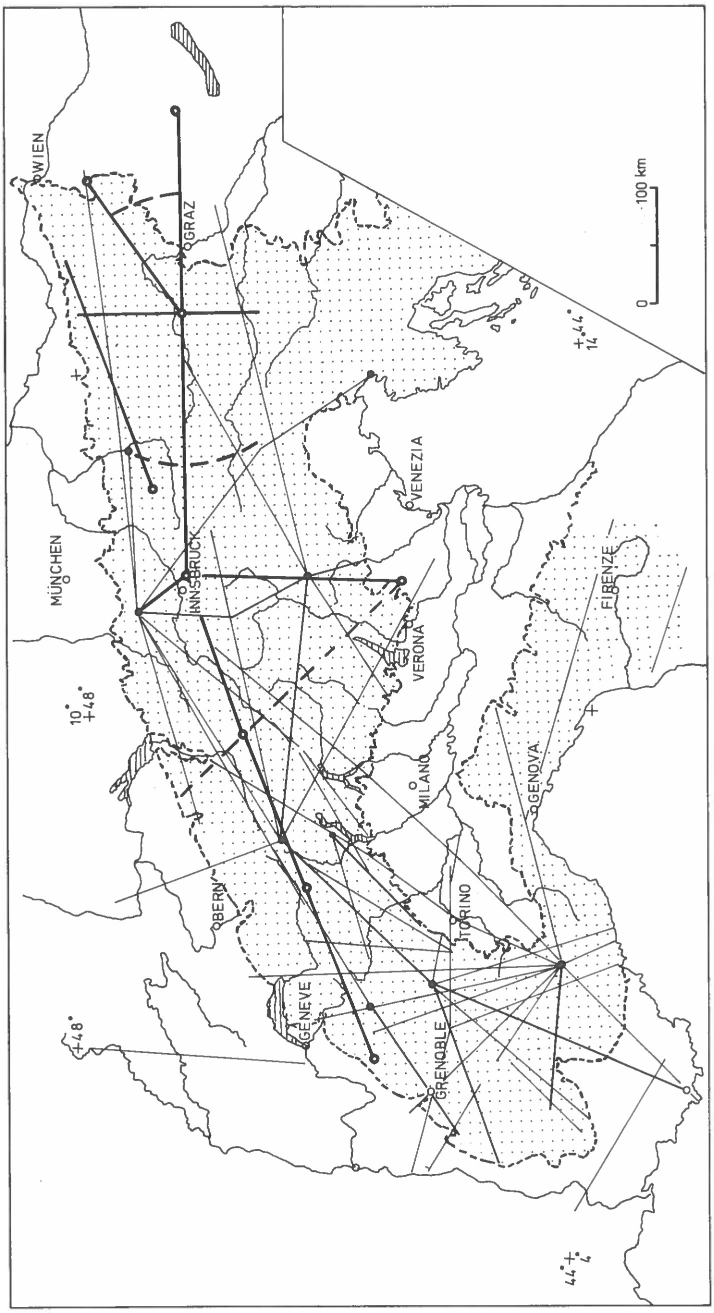

Figure 1

Position map of shotpoints and seismic refraction lines observed up to 1974 (after GIESE and PRODEHL, 1976). Thin lines represent profiles observed up to 1974, heavy lines the position of ALP 1975 profiles and fans.

GIESE and DE VISINTINI, 1971; GIESE and MORELLI, 1972; ANGENHEISTER, BÖGEL, GEBRANDE, GIESE, SCHMIDT-THOME and ZEIL, 1972; GIESE and PRODEHL, 1976). Being review articles these papers also give a rather complete compilation of the literature on the subject.

By 1970 the concentrated efforts of the various groups had greatly enhanced our knowledge of the structure of the crust beneath the Alps. Looking at Fig. 1 however one can see that coverage of the Alps with profiles was not uniform at all, but that most of the profiles traversed the Western Alps and there especially were concentrated in the region of the Ivrea zone. One must also note that the directions of the profiles generally do not follow the strike of the large scale geologic features of the Alps but rather are oriented perpendicular or at some other angle with respect to the large scale features. This is due to the fact that shotpoints were bound to the more or less accidental positions of quarries and lakes available for seismic purposes. This is one of the main reasons why, as interpretational techniques became more powerful especially through the development of ray tracing programs (GEBRANDE, 1975, 1976; WILL, 1975), some of the results obtained earlier became doubtful. It could be shown for instance that certain features of the travel time curves, which were attributed to velocity inversions in the crust, could also be caused by lateral velocity variations. Because of the wide spacing of profiles in the Eastern and Central Alps it was not possible to distinguish between lateral and vertical velocity variations. For the Ivrea zone with its dense coverage with profiles however such a distinction could be made, thus allowing to resolve the very complex crustal structure of that areas with the accuracy necessary for the development of geodynamic models (BERCKHEMER, 1968; GIESE, 1968a).

This led us to believe that a new experiment should be carried out in the Alps which should satisfy the following conditions:

(a) In order to avoid strong lateral velocity gradients the refraction line should follow the strike of the main geologic units and shotpoints should be positioned accordingly. The results to be expected from the interpretation of data recorded along such a profile could later serve as a reference for the reinterpretation of older profiles from the same area. This in the end will lead to a much more reliable model of the alpine crustal structure.

(b) The whole length of the Alpine orogen should be covered, thus allowing deeper penetration than with earlier experiments in order to obtain information on the structure of the lower lithosphere beneath the Alps.

The second condition was deemed necessary as the long range refraction seismic experiments in France in 1971 and 1973 (GROUPE GRANDS PROFILS SISMIQUES and GERMAN RESEARCH GROUP FOR EXPLOSION SEISMOLOGY, 1972; HIRN, STEINMETZ, KIND and FUCHS, 1973; HIRN, 1973; KIND, 1974; HIRN, PRODEHL and STEINMETZ, 1975) and England in 1974 (BAMFORD, FABER, JACOB, KAMINSKI, NUNN, PRODEHL, FUCHS, KING and WILLMORE, 1976) have shown a fine structure of the lower lithosphere beneath the Variscan of France and the Caledonides of England. Obviously one should also know the structure of the lower lithosphere beneath a young orogen like the Alpine one. The knowledge of the structure at that depth range should give an essential contribution to the understanding of the geodynamic evolution of the Alps and a comparison with the structures beneath older orogens should be very interesting.

Quite clearly an experiment of that scope could only be carried out as a joint venture of as many groups as possible from different countries. Therefore, in 1974 an international group met to start the planning of the new experiment. Hence, again under the auspices of the European Seismological Commission the Alpine Explosion Seismology group organized the subsequently described experiment which was named 'Alpine Longitudinal Profile 1975' (ALP 1975).

2. *The experiment*

Figure 2 shows the layout of the refraction segments of the ALP 1975 experiment. Starting at the western end, at shotpoint A (Mont Revard, France), the profile follows the strike of the Western Alps in north-easterly direction up to the south of Innsbruck. At shotpoint D (Wattener Lizum) it turns almost due east in order to follow the strike of the Eastern Alps and terminates at shotpoint F (Körmend, Hungary). In addition to the main line which is 850 km in length and which rather precisely follows the axis of the negative gravity anomaly, several shorter profiles were observed. The different profile segments were numbered. Profile segments 6, 8, 9, 10, and 12 served a double function, one as profiles with respect to shotpoints situated on them, the other as fans with respect to offsided shotpoints. Figure 3 schematically shows the system of reversed and overlapping profiles realized for the main line. The distance range of observable energy is given for each shotpoint.

Two of the shotpoints (D and E) were situated in high mountain lakes with water depths of 6 and 12 meters, respectively. Thus an effective optimization of the shots with respect to a constructive interference of the pulsations of the gas bubble and the organ pipe mode of the water body was not feasible. From previous experiences (BURCKHART and VEES, 1975), however, it could be shown that good seismic energy can be transmitted from a shallow water body by distributing the total charge over a large area on the bottom of a lake. In this case single charges of 50 kg each were laid out on a 50×50 m grid with 10 m spacing and fired concurrently. Technical details are given by ARIC (1975). Explosions with a total charge of 2.5 tons could be observed reasonably well to a distance of at least 500 km.

The shots at shotpoints A, B, C, F and H were fired conventionally from boreholes drilled especially for that purpose. However, the seismic efficiency of these shots varied rather strongly with the local geology. Shotpoints G and I were situated in quarries. Table 1 gives the technical data for all shots.

The large scope of the experiment as well as the rather rugged terrain made it

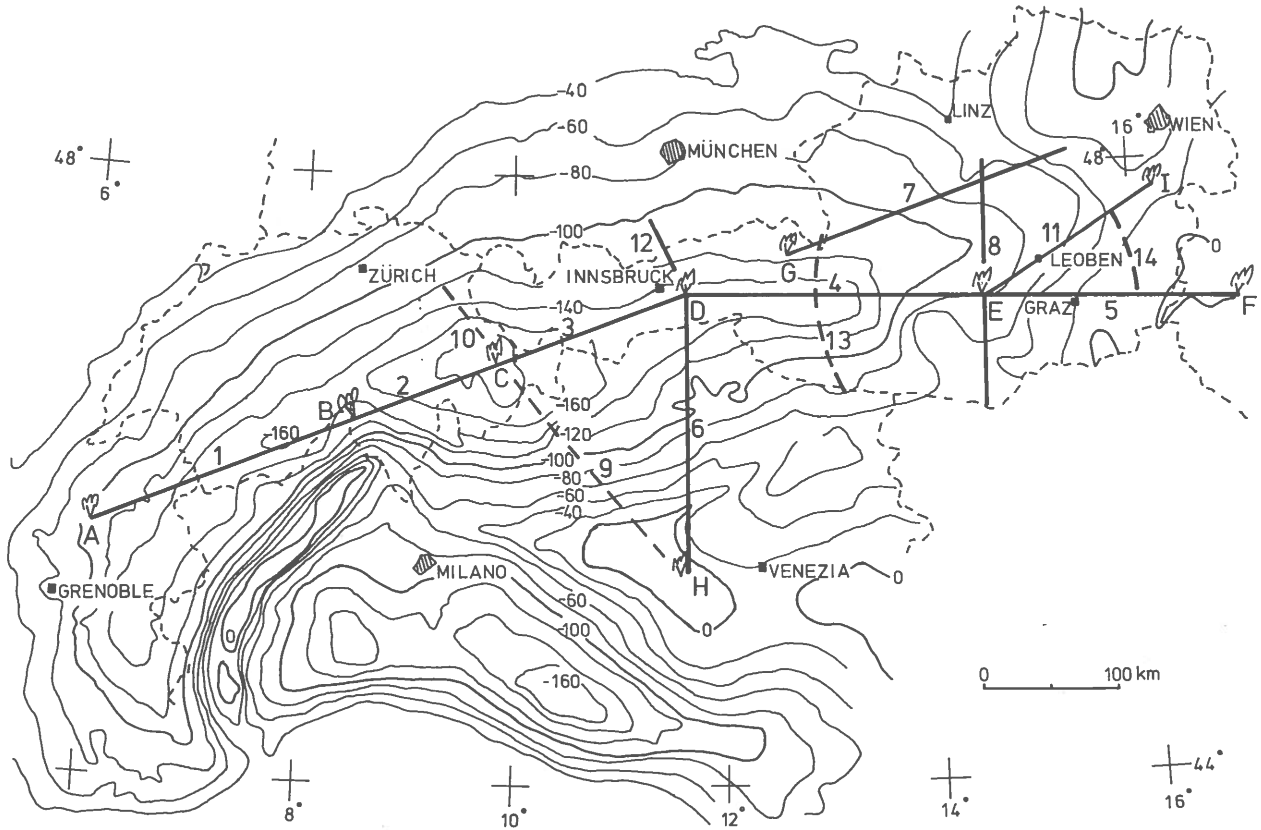

Figure 2

Simplified Bouguer gravity map of the Alps together with location of shotpoints and profiles of ALP 1975. Profile segments are numbered, shotpoints indicated by letters.

A: Mont Revard	D: Wattener Lizum	G: Hochfilzen
B: Nufenen Pass	E: Zirbitzkogel	H: Orgiano
C: Flüela Pass	F: Körmend	I: Bad Deutsch Altenburg

Contour interval of Bouguer gravity is 20 mgal. Gravity data after MAKRIS (1971) and B.G.I. (1964).

necessary to use as many recording stations as possible. Thus a total of 193 recording instruments were deployed along the segments of the profile. The total number consisted of 158 Mars 66 stations (BERCKHEMER, 1970), 7 digitally recording and fully Mars compatible PCM stations (GEBRANDE, MILLER and SCHMEDES, 1976), 5 Geostore recorders with 7 telemetered links, 5 Sprengnether ink recorders and 5 film recorders. Two 24-trace reflection instruments were used near shotpoint E for reflection work and four 24-trace reflection instruments adapted for refraction use covered the Hungarian part of the profile. All stations were equipped with 2 Hz seismometers and, with the exception of a few, namely the four types named last, calibrated to the same standard. Time signals were received from DCF (77.5 kHz), HBG (75 kHz) and in a few cases even from MSF (60 kHz).

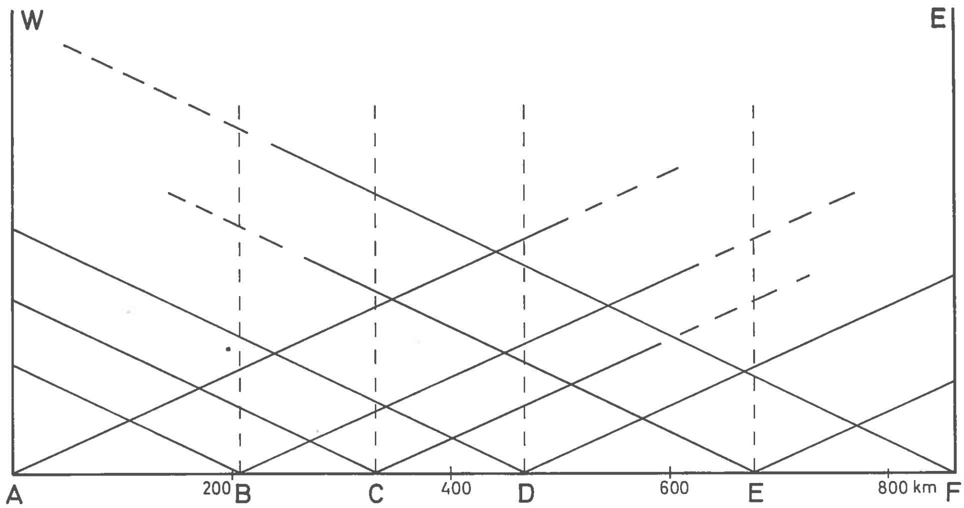

Figure 3
Simplified diagram showing scheme of observations for the main line. Solid lines: observational range with sufficient signal strength; dashed lines: range with questionable signal strength.

The whole experiment was carried out on a tight schedule during the two weeks from 8 to 20 September 1975. Stations were set up initially with a spacing of 8 km along profile segments 1 to 6, 8 and 9 and with a spacing of 10 km on profile segments 7 and 12. For the first half of the experiment the stations remained at their initial positions recording the first shots from every shotpoint. For the second half of the experiment the stations were shifted by 4 or 5 km, respectively, to occupy alternate positions on the profiles. Then the second series of shots was recorded. Finally profile segments 11, 13 and 14 were occupied by a total of 62 stations with a mean spacing of 5 km and shots E3 and I were fired.

Even if it necessitates a large number of observers and recording stations we feel

Table 1
Technical data for the ALP 1975 shots.

Shot No.	Charge (tons)	Longitude East	Latitude North	Date	Time (CET)	Elevation (m)	Type	No. of Charges
A1	2	5°59′08.7″	45°40′00.4″	12.9.75	10:31:11.52	1375	Boreholes	8
A2	4	5°59′33.1″	45°40′05.3″	17.9.75	13:01:04.53	1370	Boreholes	16
B1	2.05	8°23′21.2″	46°29′11.8″	12.9.75	10:01:02.99	2460	Boreholes	4
B2	1.38	8°23′01.6″	46°29′11.8″	15.9.75	10:01:05.47	2430	Boreholes	4
C1	0.68	9°56′46.5″	46°45′51.8″	10.9.75	12:31:15.170	2240	Boreholes	1
C2	3.3	9°56′47.0″	46°45′48.9″	17.9.75	14:01:03.83	2240	Boreholes	2
D1	1.5	11°40′40.8″	47°10′12″	12.9.75	08:01:00.63	2250	Lake	30
D2	2.5	11°40′40.8″	47°10′12″	15.9.75	09:01:00.51	2250	Lake	50
E1	1.5	14°34′21.6″	47°03′34.2″	10.9.75	08:01:00.575	2050	Lake	30
E2	2.5	14°34′21.6″	47°03′34.2″	15.9.75	08:01:01.152	2050	Lake	50
E3	1.2	14°34′21.6″	47°03′34.2″	19.9.75	13:01:01.115	2050	Lake	24
F1	1	17°01′04″	47°07′17″	10.9.75	08:31:01.870	200	Boreholes	20
F2	2	17°01′04″	47°07′17″	12.9.75	09:00:57.58	200	Boreholes	32
F3	4	17°01′04″	47°07′17″	17.9.75	09:01:01.95	200	Boreholes	60
G	0.8	12°34′03.5″	47°25′40.14″	17.9.75	12:01:01.20	1650	Quarry	10
H0	0.6	11°26′56″	45°20′35″	10.9.75	13:01:00	120	Boreholes	
H1	0.9	11°26′56″	45°20′35″	12.9.75	11:01:01.88	120	Boreholes	
H2	1.2	11°26′56″	45°20′35″	15.9.75	11:00:57.88	120	Boreholes	
H3	1.5	11°26′56″	45°20′35″	15.9.75	17:01:06.68	120	Boreholes	
I	0.6	16°55′03″	48°08′09″	19.9.75	12:00:58.31	420	Quarry	6

that the procedure of covering the whole length of the profile with stations at all times during the experiment with double the mean spacing and moving all stations only once offers various advantages. Firstly the necessary travel of observers is kept at a minimum which reduces the total field time and secondly every shot will be observed as far as the signal to noise ratio permits. Thus no data are lost due to a possibly insufficient length of the recording arrangement as might be the case with other station distributions. Finally, should one of the shots fail, at least the other one from the same shotpoint may be recorded along the whole profile, whereas if all stations were used as a movable array with a closer spacing of stations and shifted *en bloc* along the profile a misfired shot would have caused a gap of some 400 km in the data.

In addition to the observations in the Alps the shots from shotpoint F and E were recorded by the Czechoslovakian and Polish groups along the line Komarno–Zakopane–Lublin. This line is not shown in Fig. 2 and results will be presented elsewhere. During the time of the experiment the Geostore stations were run continuously, thus recording a number of microearthquakes and a few larger events. Some of them could also be recorded by 5 event-triggered PCM stations. The Geostore stations had been distributed on the profiles in the form of a diamond shaped array with a diameter of approximately 100 km. As these stations remained fixed, they acted as reference stations for the various shots.

It was quite clear from the start that recording sites had to be chosen as close as possible to the straight lines between the shotpoints in order to avoid effects caused by lateral displacements which could easily make correlation of seismic phases rather difficult. Therefore, most of the recording sites were searched for and selected during the months prior to the experiment. The criteria for the selection were with decreasing priority: low ground noise level, good time signal reception – in the Alps topographic effects quite often cause poor radio reception –, position with respect to the main line and easy accessibility. Satisfying the first three criteria made an easy accessibility quite frequently impossible. Many recording sites had to be chosen off the main roads high up in the mountains as valleys are mostly filled with young sediments which together with the dense population of Alpine valleys cause a rather high ground noise level. Some stations had to be backpacked when no means of mechanized transport like cable cars or chair lifts was available. Such stations were manned by two observers.

During the experiment the operations were coordinated from a central headquarters at Innsbruck, which held contact with shotpoints, recording stations and other interested or assisting groups by telex and telephone either directly or through the various sub-headquarters one of which was established for each country (Chamonix, Zürich, Innsbruck, Leoben, Trieste, Budapest). These centers also provided for regular collection and playback of magnetic tapes in order to have a running check on instrument performance and quality of recordings. The problem of communicating with individual observers was greatly diminished by the fact that the Austrian radio network agreed to broadcast special news for the observers three times daily over all its FM stations thereby reaching at least one half of all observers. The rather tightly knit organization and the continuous control of data enabled rapid changes and improvements of the original program.

3. The data

During the field experiment analog playbacks of about 80% of the data had been made and a few preliminary seismogram sections were assembled. However, to facilitate data exchange and to enable further and more sophisticated data processing by digital techniques it was decided to digitize all data centrally. Digitization and primary processing of Mars 66 data was carried out on a Raytheon 704 computer at the Geophysikalische Institut Karlsruhe during a five month period starting in December 1975. The data were sampled at a rate of 400 Hz using the pilot frequency of the Mars 66 instruments to control the rate of digitization thereby eliminating tape wow and flutter. The Geostore data were digitized at Edinburgh using the recorded control frequency and resampling at 100 Hz. Typically the recordings were digitized from at least 10 seconds prior to the expected first arrival and ending at least 10 seconds after the expected *s*-wave arrival. After digitization all data were processed with a set of programs in order to determine the exact starting time of digitization and the exact digitization rate from the recorded time signal. Even rather poor time signals could be used to recover time information by using correlation techniques. With these informations the seismic information could be demultiplexed and the single traces reduced to time series starting at a known time. After preliminary plots for the control of proper processing of the data, they were filtered with an anti-aliasing filter (90 Hz low-pass filter) and resampled at 5 ms intervals. After a second low-pass filter with a cutoff frequency of 30 Hz and subsequent resampling at 10 ms intervals the data were further reduced resulting in time series which could be plotted within a reasonable time. The application of a 1 Hz high-pass filter eliminated low frequency noise in the signals. Figure 4 shows examples of the data at this stage of processing – band-pass filtered 1–30 Hz. In the next step seismogram sections were plotted with these raw data in order to determine whether further filtering would facilitate the correlation of travel time branches. For most of the data a band-pass filter of 1–12 Hz with a rather flat high frequency cutoff gave the 'best' results with respect to the overall features of the seismogram sections. First arrivals, however, may already become masked a little as their higher frequency content is lost. Yet the use of differently filtered record sections is a great help in finding the most probable system of travel time branches. More sophisticated data processing methods may also easily be applied to the data. Figure 5 shows a record section filtered with a band-pass filter of 1–12 Hz and one can easily see, how the P_MP phases become discernible very well in the distance range 70 to 120 km.

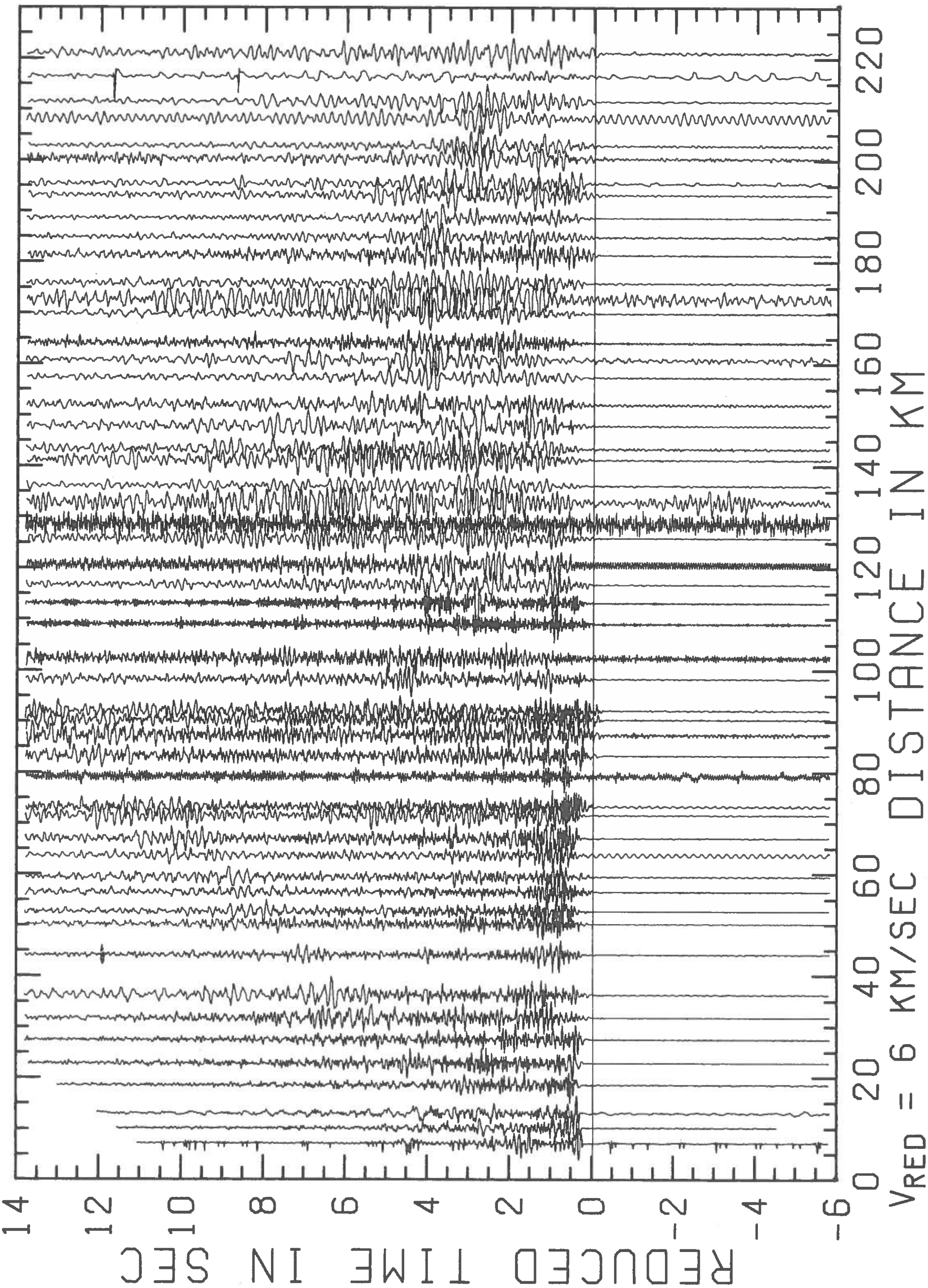

Figure 4
Record section of profile segment 4, shotpoint E, band-pass filtered 1–30 Hz.

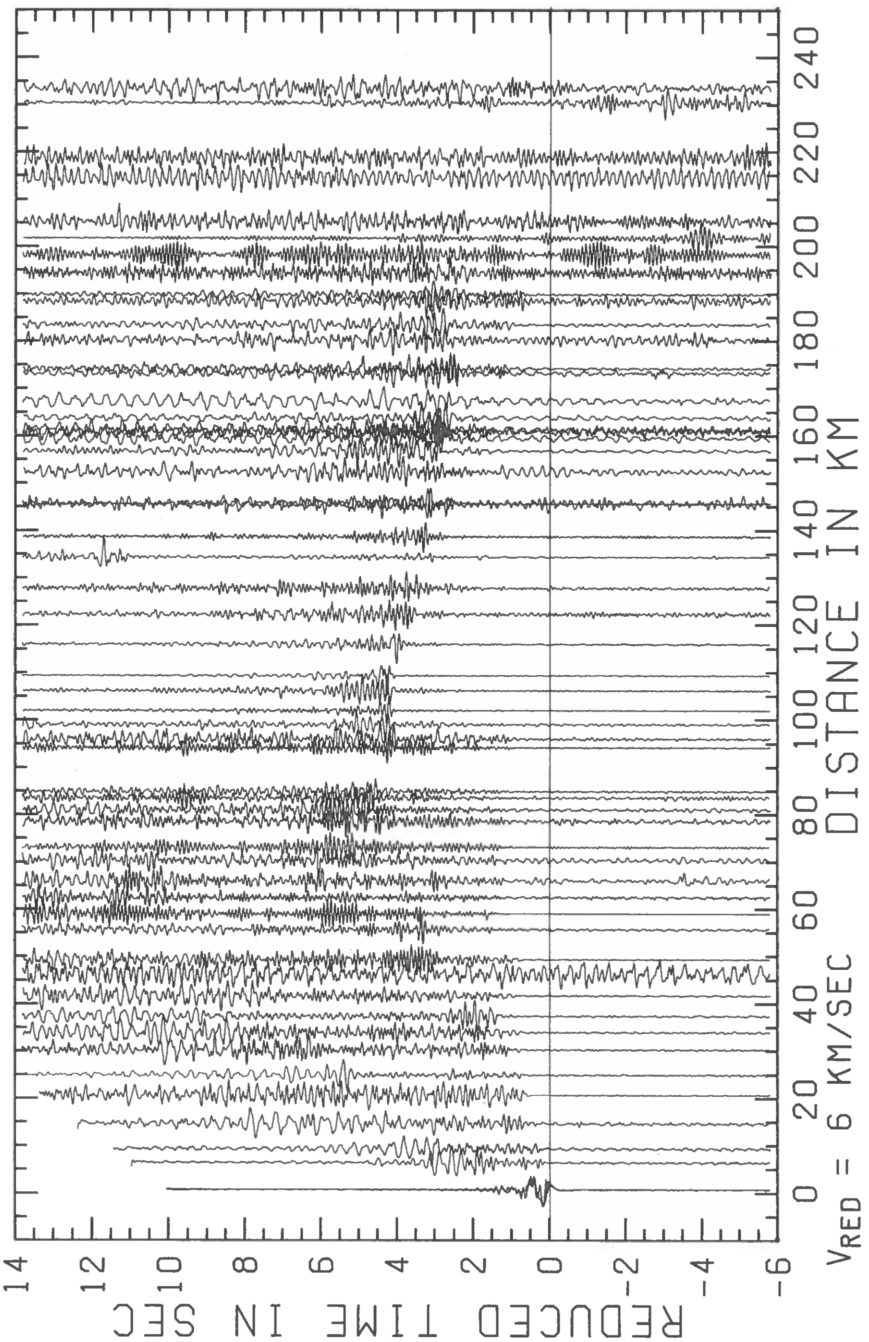

Figure 5
Record section of profile segment 1, shotpoint A, band-pass filtered 1–12 Hz.

While Figs. 4 and 5 are record sections of individual profile segments, Fig. 6 shows the complete record section for the main profile (segments 1 to 5) from shot-point F. The reduction velocity for that section is 8 km/sec and one can clearly identify signals out to a distance of about 620 km. At the larger distances further processing will be required to discriminate between signals and noise.

4. *Preliminary results*

With the setup of reversed and overlapping profiles (Fig. 3) it was intended to obtain detailed and reliable information on the structure of the crust as well as on the fine structure of the lower lithosphere. To obtain this information it is necessary to use refined and time consuming interpretation techniques. At the present stage we want to present results of a very preliminary nature only. Figure 7 shows a vertical cross section of the alpine crust along the main profile. The maximum depth to the Moho-discontinuity is plotted together with the mean velocities for the crust. These quantities were obtained using the formulae given by GIESE (1968b).

$$Z_{\max} = \frac{x}{2}\sqrt{\frac{t}{x}\frac{dx}{dt} - 1} \qquad \text{and} \qquad \bar{v} = \sqrt{\frac{x}{t}\frac{dx}{dt}}$$

with x being the distance for the critical reflection, and t the traveltime at that distance.

Experience has shown that $Z_{\max}$ and $\bar{v}$ obtained by these formulae give a good first approximation to the real values whenever the critical reflection point and the apparent velocity can be determined accurately. The results obtained in the ALP 1975 project are in good agreement with determinations published earlier (LABROUSTE, BALTENBERGER, PERRIER and RECQ, 1968; CHOUDHURY *et al.*, 1971; ANGENHEISTER *et al.*, 1972; SOLLOGUB, PROSEN and Co Workers, 1973; KAHLE, KLINGELE, MUELLER and EGLOFF, 1976; GIESE and PRODEHL, 1976). The results of these authors are marked by crosses in the vertical section and all lie at shallower depths than those calculated with the method mentioned above as is to be expected. The circles plotted indicate the positions along the profile at which $Z_{\max}$ is valid and their diameters give the estimated error for the maximum depth. The dashed parts of the line indicate the extrapolation of the Moho depth between the individually determined values. The Bouguer anomaly plotted in the top part of Fig. 7 is taken from MAKRIS (1971). The trend of the anomaly is roughly the same as the one of the Moho although there seems to exist a systematic difference between the Eastern and Western Alps. This may be caused by differences in the structure of the crust above the Moho. The relatively steep increase in crustal thickness at both ends seems to be corroborated by the observed apparent P_n velocities which approximately yield the same dip angles as indicated in the figure.

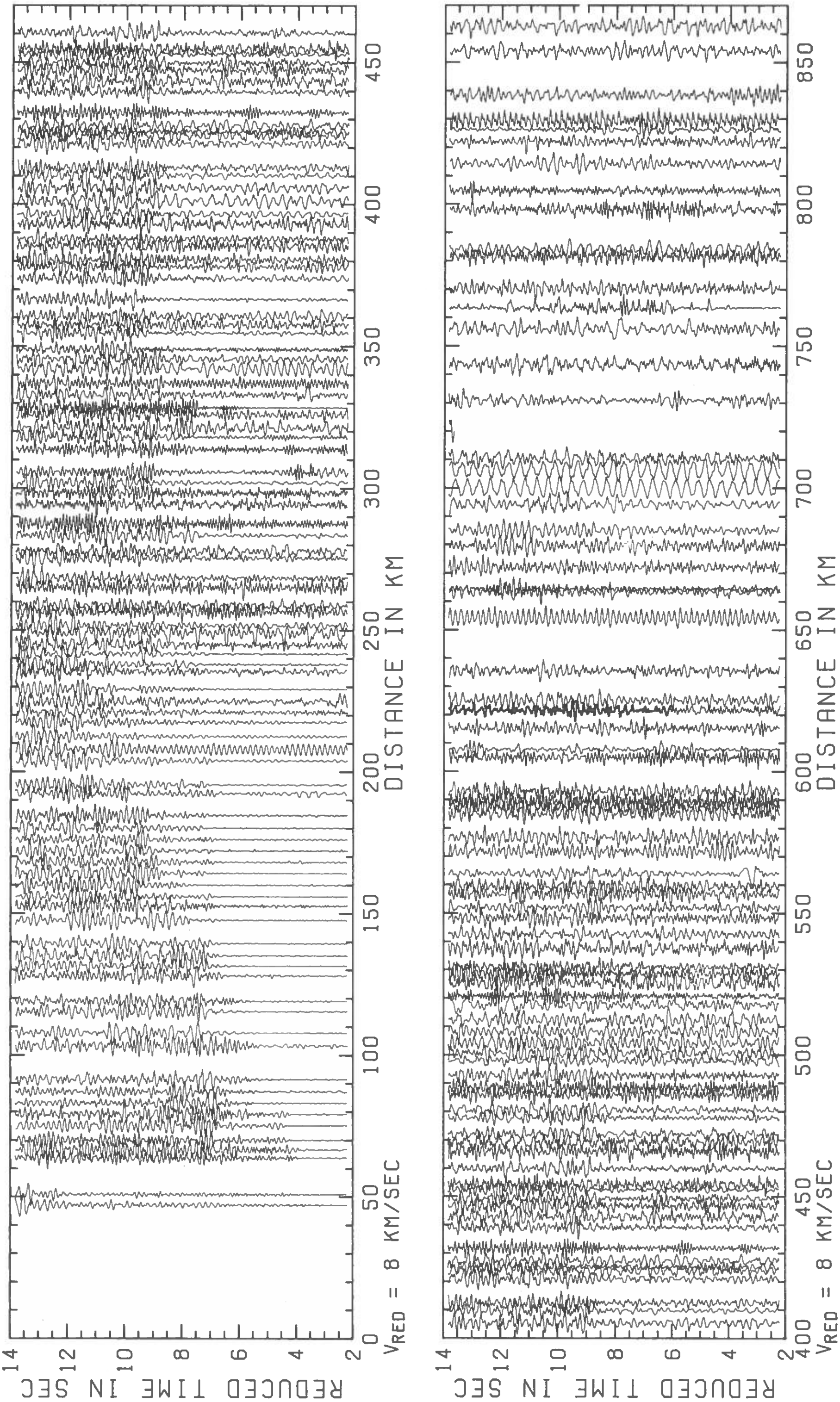

Figure 6

Record section of the main profile (segments 1 through 5), shotpoint F. The top and bottom part overlap in the distance range 400 to 470 km.

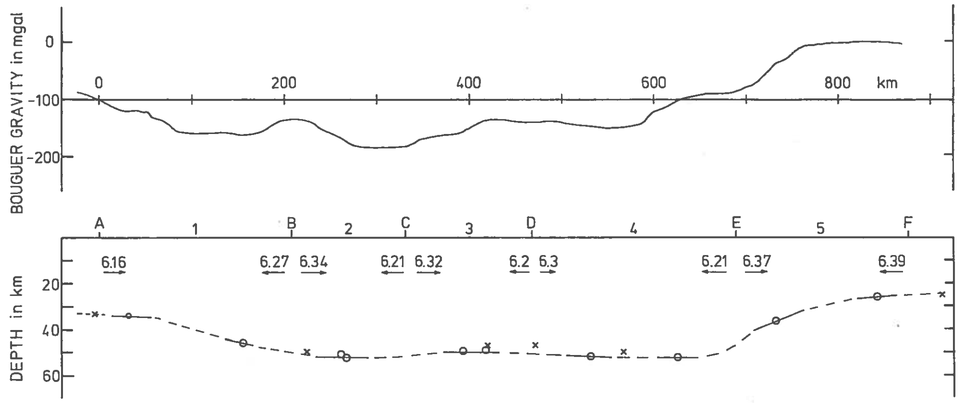

Figure 7
Preliminary cross section of the crustal structure along the profile as derived from these measurements. See text for methods. Numbers with arrows give mean crustal velocity. Maximum depth values are plotted. Bouguer anomaly after MAKRIS (1971) and B.G.I. (1964).

A slightly more detailed investigation, however, reveals, that although the mean velocity for the crust is about the same or exactly the same as was previously known, the distribution of *p*-wave velocities with depth is quite different from the earlier models at least for the Eastern and Central Alps. Figure 8 shows three velocity–depth functions. The dashed one was calculated for plane layering beneath shotpoint D from observations along profile segments 4 and 5 (Fig. 2). The travel time curves

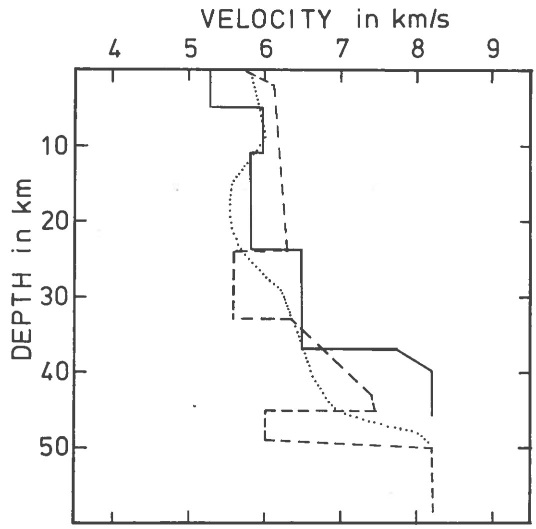

Figure 8
Velocity–depth functions. Solid line: profile segment 1, shotpoint A; dashed line: profile segments 4 and 5, shotpoint D; dotted line: after ANGENHEISTER *et al.* (1972).

calculated for that particular velocity depth function are shown in Fig. 9. The agreement between calculated and observed travel times seems to be satisfactory if one keeps in mind that lateral velocity variations are not taken into account. Whereas earlier models (CHOUDHURY *et al.*, 1971; ANGENHEISTER *et al.*, 1972) contained a low velocity zone between approximately 10 and 25 km depth (e.g. dotted velocity–depth function in Fig. 9), the model presented here is characterized by a rather thick layer with a mean velocity of 6.2 km/sec in the uppermost part of the crust (dashed line in Fig. 9). The lower crust is intercalated by two velocity inversions, the lower of which is situated immediately above the Moho. Such low velocity zones just above the Moho have already been suggested by GIESE (1972) and GIESE and PRODEHL (1976) for some areas of the Eastern Alps. It is seen that the depth range of the upper low velocity zone on the evidence of the new data must be changed which obviously will have to be taken into account in geodynamic considerations. This change of the depth range seems to be valid for most of the main line except for the westernmost segment 1 (Fig. 2). The solid velocity–depth function of Fig. 8 was calculated for profile segment 1 shotpoint A, again under the assumption of plane layering. There the low velocity zone is at a depth between 12 and 24 km, which is substantially higher than elsewhere along the profile. Yet this velocity–depth distribution must also be viewed as a first approximation as the assumption of plane layering may not be valid because of the downdip of the Moho (Fig. 7). The use of model calculations with two-dimensional velocity distributions will be necessary to resolve this problem. The lateral variations of the crustal structure in that area can easily be seen from the undulations of the correlated phases P_MP and P_n (Fig. 10).

As long as the detailed crustal structure is not yet resolved it is not possible to determine reliable models for the upper mantle from the Alpine long-range data because they are strongly influenced by the structure of the crust. Therefore, no attempt is made to give an interpretation for these data. Looking at Fig. 6, however, one can see that the P_n phase dies out around 360 km. Another phase with a higher apparent velocity and large amplitudes can be correlated between 300 km and 440 km and perhaps a second one between 420 km and 620 km. Beyond that range no correlation is possible due to lack of energy. There is a chance however that further processing – using for instance polarizing filters – will yield better results also at those distances. Similar phases may also be correlated on other record sections.

5. *Concluding remarks*

This is the first paper of a series of papers on ALP 1975. The papers to come will describe the results in much greater detail and hopefully much more accurately. The aim of this paper was to describe the experiment and give some preliminary results. The data presented here are only in a first stage of evaluation and will be further processed and interpreted in more detail by the authors.

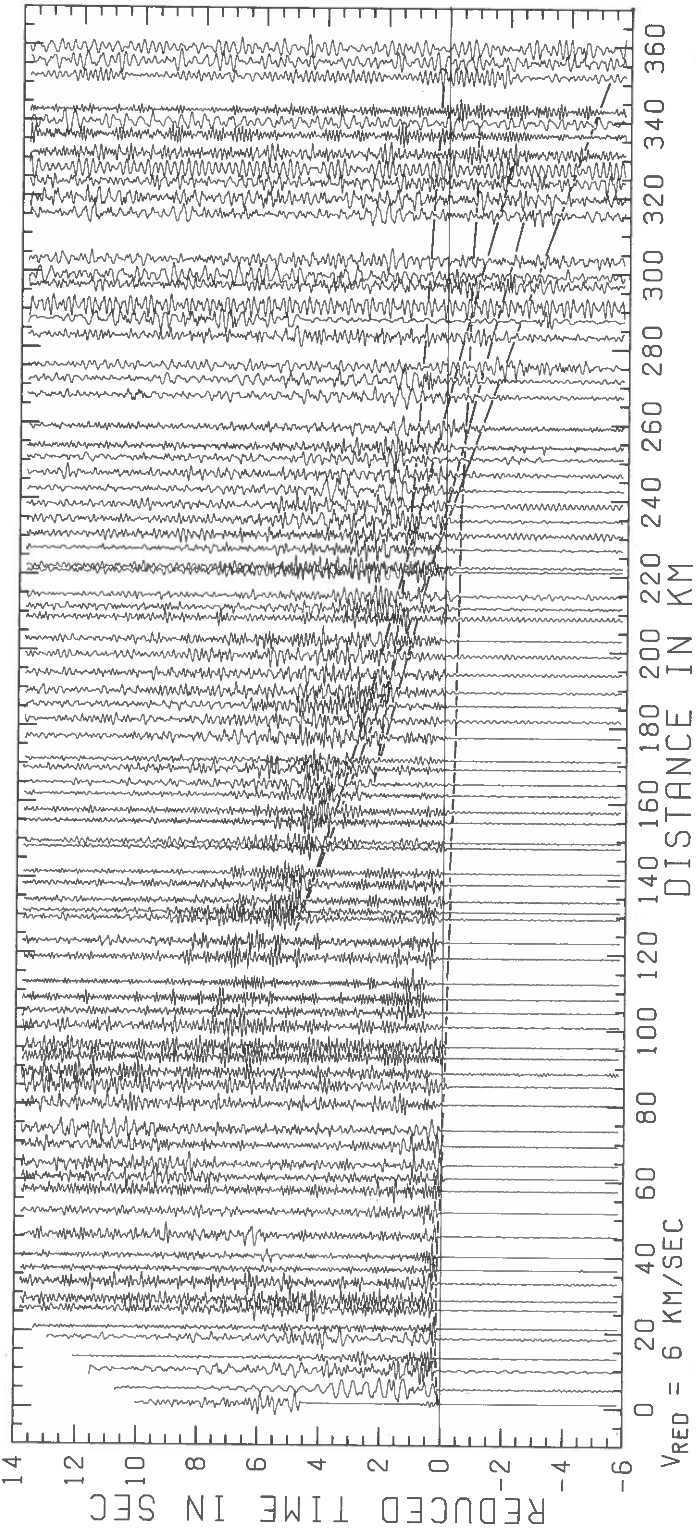

Figure 9

Record section of profile segments 4 and 5, band-pass filtered 1–12 Hz with travel time curves calculated from the dashed velocity–depth function of Fig. 8.

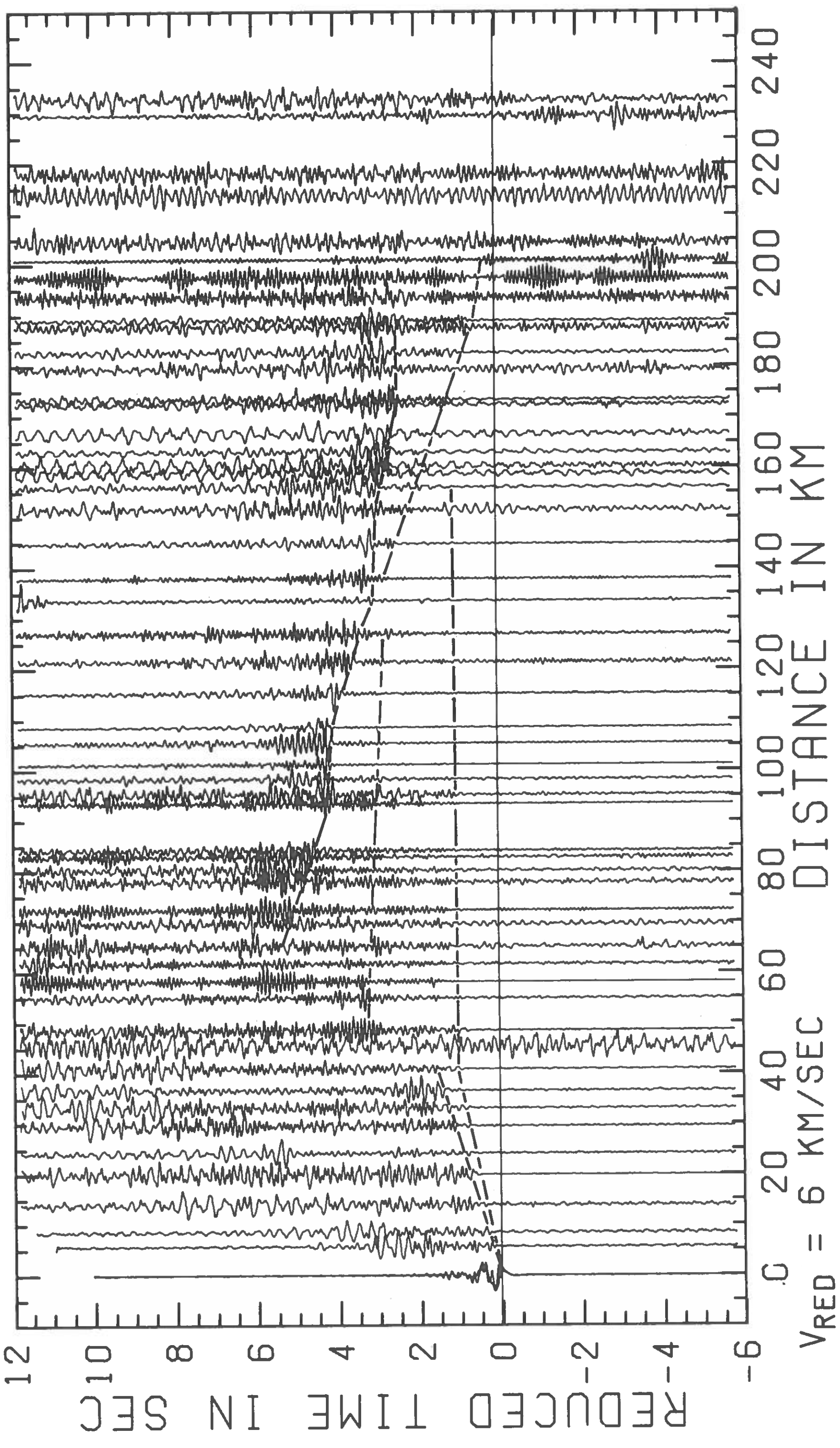

Figure 10

Record section of profile segment 1, shotpoint A, band-pass filtered 1–12 Hz with correlated travel time branches. Note undulations of P_MP and P_n branches indicating influence of lateral variations.

We may state that the experiment was quite successful. It yielded good quality data, which will enable us to obtain reliable information on the structure of the lower lithosphere underneath the Alps for the first time and to further clarify the structure of the crust. In addition the data obtained proved that it is possible to plan and successfully carry out an experiment amongst groups from nine different countries.

Acknowledgements

The experiment was a joint project of the cooperating countries which was made possible by different funding agencies which financially supported the participation of their respective countries.

Austria: Bundesministerium für Wissenschaft und Forschung. *France:* Institut National d'Astronomie et de Géophysique. *Germany:* Deutsche Forschungsgemeinschaft. *Great Britain:* Natural Environmental Research Council. *Hungary:* Hungarian Geophysical Institute 'Roland Eötvös'. *Italy:* Consiglio Nazionale delle Ricerche. *Switzerland:* Fonds National Suisse de la Recherche Scientifique, Swiss Federal Institute of Technology, Swiss Army. *Czechoslovakia:* Geofizika Narodne Podnik. *Poland:* Polish Academy of Sciences.

Obviously an experiment of such a scope could not have been carried out without the assistance and technical support of a large number of individuals and of state or private institutions and it is impossible to acknowledge but the most important assistance in the countries where shots were fired.

AUSTRIA: The continuous support of Prof. Dr. F. Steinhauser, chairman of the Austrian national committee of the Geodynamics project is gratefully acknowledged. The Landeshauptleute of Steiermark and Tirol, Dr. Niederl and Wallnöfer, the Bezirkshauptleute of Judenburg and Schwaz, Drs. Schönegger and Weißgatterer with members of their staff gave permission for the shots in the lakes at shotpoints D and E; the Austrian Army gave technical and logistic support – both D and E are situated on Army training grounds – and the furtherance of the project by the minister of defence Brigadier K. H. Lüttgendorf and Oberst Schön as well as the help in the field by the local commanders Oberst Knoll, Oberst Eisenbach and Hauptmann Stieger is gratefully acknowledged; the Österreichische Amerikanische Magnesit Werke and Dr. Weidinger (Mrs.) gave permission to use the quarries at Hochfilzen and Bad Deutsch Altenburg for ALP 1975 shots. The Österreichische Bundesforstverwaltung gave permission to use the forestry roads and the ORF broadcast special news for the observers. The Bundesamt für Eich- und Vermessungswesen and the Zentralanstalt für Meteorologie und Geodynamik gave logistic support.

FRANCE: The assistance of the local authorities in all matters concerning the shotpoint at Mont Revard is gratefully acknowledged.

HUNGARY: The active support by members of the Hungarian oil and gas trust is gratefully acknowledged.

ITALY: Particular thanks are due to Italcementi, Bergamo, for having authorized the shooting site in their quarry at Orgiano (Vicenza); to the Corpo Miniere, Padova, for the same authorization; to the Servizio Sicurezza Mineraria, Ministero Industria, Roma, for the security controls in the field; to the local civil and military authorities in Orgiano and Vicenza; and to Mr. Ghiretti, Parma, for the enthusiastic cooperation in the drilling of the boreholes.

SWITZERLAND: Thanks are due to the Swiss Army for technical and logistic support at shotpoints B and C and also to the local civil authorities, the Landschaft Davos, Gemeinde Luzein (GR) and the Gemeinde Ulrichen (VS).

Last but not least we thank the participants in the field work, who by their personal engagement and effort under sometimes quite severe circumstances contributed so much to the success of the experiment. Their names are given in the appendix.

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Appendix

The following institutes were responsible for organizing the experiment:

Austria: Lehrkanzel für Geophysik, Universität Wien
France: Laboratoire de Géophysique Interne, Université de Grenoble
Germany: Institut für Allgemeine und Angewandte Geophysik, Universität München (overall coordination)
Great Britain: Geophysics section, University of Birmingham
Hungary: Hungarian Geophysical Institute 'Roland Eötvös'
Italy: Istituto di Miniere e Geofisica applicata dell' Università Trieste
Switzerland: Institut für Geophysik, ETH Zürich

Participants:

Berlin: Boldt, Bram, Gorling, Hinze, Krause, Reichert, Renger, Röwer, Schmidt, Schütte, Schwarz, Steinhage, Wigger. *Birmingham:* Brett, Hackney, Hill, King, Nunn, Owens. *Bochum:* Will. *Budapest:* Jaanvari, Korvin, Lakner, Mituch, Petrovics,

Posgay. *Catania:* Cosentino, Di Paola, Leotta, Lombardo, Riuscetti, Villari. *Clausthal-Zellerfeld:* Burkhardt, Buntebarth, Herbst, Hoffmann, Linnenkohl, Rothfuchs, Vees. *Edinburgh:* Bamford, Chappel. *Frankfurt:* Bayer, Hassan, Miethke, Reichenberger, Schaarschmidt, Scherneck. *Genova:* Carenzo, Eva, Ferro, Merlanti, Siri. *Grenoble:* Bernard, Boulange, Ferraris, Gamond, Hatzfeld, Marie, Menard, Mercieca, Perrier, Plotto, Robert, J. P., Robert, Ph., Thouvenot. *Göttingen:* Klinge, Krummheuer, Kuchta. *Hamburg:* Dornbusch, Klußmann, Krüger, Möller, Müller, Nortmann, Schlothauer, Sümer, Zerna. *Hannover:* Behnke, Dohmann, Ifkovits, Koschyk, Weitmüller, Völkel. *Karlsruhe:* Diestl, Gilg, Gothe, Haggag, Hörnchen, Kaminski, Kind, Prodehl, Schott, Volk, Weingärtner. *Kiel:* Lange, Lohr, Schulze, Stümpel, Vetter, Weinrebe. *Leicester:* Coward, Khan, Maguire, Mayhew, Whitcombe. *Leoben:* Atzmüller, Groß, Mauritsch, Schmid, Schmöller, Wallach, Weber. *Milano:* Amoretti, Carli, Carrara, Colombi, B., Colombi, R., Di Martino, Epifani, Ferraris, Fornaciari, Franciosi, Maccagni, Macchi, Marcellini, Pensieri, Polizzi. *München:* Ackermann, Angenheister, Beblo, Berktold, Block, Bühler, Dorner, Förtsch, Fuchs, Führer, Gebrande, Haak, Hartfeil, Kemmerle, Klemm, Koch, Lehner, Lüdtke, Martinez, Miller, Mirwald, M'Seddi, Petersen, Pohl, J., Pohl, W., Rankl, Schärmeli, Schmedes, Schmidbauer, Schönharting, Schult, Schwolow, Soffel, Strößenreuther, Thuringer, Zeil, Zinsser. *Napoli:* Corrado, Del Pezzo, D'Isanto, Guerra, Esposito, Lo Bascio, Russo, Scarpa, Talarico. *Paris:* Bert, Brefort, Carpels, Cisternas, Delmond, Eschenbrenner, Genest, Godecaux, Michel, Recq, Ruegg, Simonin, Vadell, Veinante, Verhille, J., Verhille, R. *Strasbourg:* Jochem. *Stuttgart:* Ganitta, Keppler, *Swansea:* Bayerly, Llewellyn. *Trieste:* Morelli, Nicolich, Paganini, Zanutti and 3 students. *Vienna:* Aric, Genser, Golser, Gutdeutsch, Klinger, Köttritsch, Osterode, Seiberl, Steinhauser. *Zürich:* Ansorge, Baer, Berger, Bodmer, Boller, Egli, Gruber, Klingelé, E., Klingelé, F., Lamson, Mueller, Pavoni, Scriba, Sprecher, Streckeisen, Werner, Wielandt.

The following Institutes provided equipment:

Universities of Berlin, Birmingham, Bochum, Catania, Clausthal-Zellerfeld, East Anglia, Edinburgh, Frankfurt, Genova, Göttingen, Hamburg, Innsbruck, Karlsruhe, Kiel, Leicester, Leoben, Milano, München, Münster, Napoli, Paris, Stuttgart, Swansea, Trieste, Vienna, Zürich. Niedersächsisches Landesamt f. Bodenforschung, Hannover; Geologisches Landesamt Nordrhein-Westfalen, Krefeld; Natural Environmental Research Council; Hungarian Geophysical Institute 'Roland Eötvös'.

(Received 12th October 1976)

Contribution No. 184 within a joint research programme of the Geophysical Institutes in Germany sponsored by the Deutsche Forschungsgemeinschaft (German Research Association):

Contribution No. 143, Geophysikalisches Institut, Universität Karlsruhe

Contribution No. 226, Institut für Allgemeine und Angewandte Geophysik, Universität München
Contribution No. 167, Institut für Geophysik, ETH Zürich
Contribution No. 11, Istituto di Miniere e Geofisica applicata Università Trieste