The Swiss Alps constitute a bivergent orogen straddling an asymmetric collision zone. Lithospheric mantle and lower crust of the European part of the Eurasian plate were subducted beneath the Adriatic plate during convergence and subsequent continental collision.
The upper crust was peeled off in fragments and stacked to form the spectacular nappe structures and external basement uplifts so characteristic for the Alpine orogen.
The novel tectonic model of the deep crustal structure of the Alpine collision zone is the result of an integration of seismic reflection and refraction data and structural data. Besides data gathered from the crust/mantle boundary, significant new insight was gained from the shallower structures. This includes 3D subsurface mapping of Alpine nappes and basement uplifts, as well as valleys incised deeply into the bedrock to levels several hundreds of meters below the present sea level. The structure of the Alps is also discussed in the framework of the geodynamic evolution – from Mesozoic sedimentation to Cenozoic subduction and collision.
NRP 20 involved researchers from the Swiss Universities and the Federal Institute of Technology, as well as earth scientists from industry. Funding from the Swiss National Science Foundation was subsequently backed up by contributions from the participating universities, from the Federal Institutes of Technology and from industry.
This book will interest students and researchers eager to have an up-to-date view of the Alpine orogen, especially its structure and evolution, as a typical example of a continental collision zone. The presentation of the full seismic sections, their geological interpretation, as well as geological profiles will interest readers not only in the field of geophysics and geology, but in earth sciences in general.

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Results of NRP 20

Deep Structure of the Swiss Alps

Results of NRP 20

Editors

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P. Heitzmann

St. Mueller

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Birkhäuser

Prof. Dr. Stephan Mueller, director of the Institute of Geophysics, ETH Zürich for many years and co-editor of this atlas died on February 17th, 1997. He was one of the main initiators of the National Research Program NRP20 on the "Deep Structure of Switzerland" and of the corresponding international project "European Geotraverse".

In addition, Stephan Mueller was a member of the group of experts to the NRP20 program and one of the principal investigators.

We express our respect and sincere thanks to Stephan Mueller for his efforts and continuous support of this project and we consider this atlas part of his legacy.

The editors

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Cover photograph

The photo of the Swiss Alps in the Valais region displays (from left/east to right/west) the peaks of Monte Rosa, Breithorn, Matterhorn, Dent Blanche and Weisshorn.

The summit areas of Matterhorn, Dent Blanche and Weisshorn are erosional remnants of a large thrust sheet of crystalline basement derived from the Adriatic microplate, a spur of the African plate. This thrust sheet overlies a nappe complex that evolved from the subduction of the Piemont ocean and that extends from Breithorn to the lower slopes of Matterhorn, Dent Blanche and Weisshorn. Monte Rosa is carved out of crystalline basement pertaining to a still lower thrust sheet derived from the Briançonnais continental fragment. This entire nappe pile overlies the nappe stack derived from the Eurasian plate, which is buried deeply beneath the area of the photograph, as was imaged by seismic experiments of NRP 20.

© Photograph by Willi Burkhardt, Buochs, Switzerland

Contents

Deep seismic profiling

Seismic sections through the Alpine foreland

Seismic sections through the Alps

Geologic structure and evolution of the Alps

Dynamic Alps

Lithospheric and crustal scale interpretation

List of plates

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Preface

The objective of the National Research Program 20 (NRP 20), funded by the Swiss National Science Foundation, was to explore the deep structure of the Swiss Alps combining geophysical and geological methods. The data were collected between 1986 and 1993. Processing and interpretation of the data involved over 50 researchers from Swiss universities and from industry. The aim of this Atlas is to draw all this work together into a coherent compilation of the geological and geophysical data, their interpretation and integration into the tectonic evolution of the Swiss Alps. This turned out to be a difficult task.

The more integrative studies depended on the availability of the interpretations of other projects. This led to postponement of the early deadlines - much to the dismay of those authors who finished their work in due time, and who saw their results slowly getting "outdated".

Within the Atlas the reader will find differing interpretations of the same data sets for some of the seismic lines. Although the existence of several interpretations for one single geophysical data set is rather the rule than the exception, it would have been preferable to show such contrasting interpretations side by side. This is where the existence of "schools of thought" influenced the compilation of this Atlas in a somewhat negative way: contrasting ideas ultimately had to be presented in separate chapters. We tried to overcome this shortcoming and guide the readers by adding the appropriate cross references. The book is a team effort, and the active participation of individual authors and co-authors occurred to variable degrees.

The Atlas is divided into 25 chapters, each of which is independent enough to be read on its own. Apart from chapter 1 these chapters are grouped into 6 thematic parts. The six parts and the chapters are given in approximate chronological order concerning the production of data and the state of knowledge.

Chapter 1 of the Atlas is an introduction, highlighting the history of NRP 20. This introduction also contains an overview of the geology of the Swiss Alps and their deep structure as derived from geophysical data.

The production of seismic sections is placed in the first part, called *Deep seismic profiling.*

Chapter 2 summarizes the acquisition of the seismic reflection data, including details about the recording parameters. NRP 20 applied both Vibroseis and explosion seismology to explore the shallower and deeper crustal features.

Processing of these data is discussed in **chapter 3**. Apart from standard processing techniques, special attention had to be paid to the effects of lateral heterogeneities and 3D-geometry of the subsurface structures. A particularly useful procedure involved the transformation of wide-angle data gathered from refraction experiments into "normal-incidence" sections.

Chapter 4 deals with the processing related to displaying the seismic reflection data. A new method of generating automatic line drawings was developed and applied to all the NRP-20 lines. These automatic line drawings turned out to reproduce the essential information contained in the seismic data, and produced a crisp image (rather than the dense image of conventional plots).

Chapter 5 presents the seismic refraction data carried out in the framework of NRP 20 and the European GeoTraverse (EGT). The first section, 5.1, contains the essential information on data acquisition and processing. The integration of these data into the network of seismic reflection lines and the 3D crustal structure is discussed in section 5.2. Carefully controlled migrations proved to be essential. A careful combination of near-vertical reflection and refraction data (the two methods are complementary, and can't replace each other) then allowed the construction of a 3D crustal model.

In **chapter 6** results from laboratory determined seismic velocities are given. Samples from the areas covered by the seismic survey were analyzed. The data highlight the type of interfaces between contrasting lithologies that represent potential reflectors.

The seismic sections and their geologic interpretation occupy the following two parts of the Atlas, named *Seismic sections through the Alpine foreland* and *Seismic sections through the Alps*. The chapters within these two parts represent the backbone of the Atlas, containing the essential new data regarding the deep structure of the Alps. *Seismic sections through the Alpine foreland* is grouped into two chapters, one covering the Jura Mountains, the other the Molasse Basin.

Chapter 7 covers three study areas in the Jura Mountains. In section 7.1 a reinterpretation of industry lines shed new light on the internal structure of the Folded Jura of the Neuchâtel area. Here the role of thrust faults underlying major anticlines had previously been underestimated. Some of the folds could be interpreted as fault-propagation folds, with a detachment in the Muschelkalk evaporites. Section 7.2 discusses the Tabular Jura around Basel. A seismic line through this Basel Jura images the Moho on the southern flank of the Black Forest-Vosges basement uplifts and suggests the presence of Late Paleozoic troughs underneath the Tabular Jura. The internal structure of the Folded Jura south of Basel and its relation to underlying Late Paleozoic troughs is the topic of section 7.3. Iterative palinspastic reconstructions allow the approximate determination of the 3D geometry of the basement beneath the Folded Jura.

The deep structure of the Swiss Molasse Basin was studied by means of two cross sections discussed in **chapter 8**. The seismic data are industry lines, which were partly reprocessed in the framework of NRP 20. In eastern Switzerland the foreland basin thickens towards the Alps; a triangle zone separates the gently dipping Plateau Molasse from the Subalpine Molasse, which consists of an imbricate stack of thrust sheets. In western Switzerland this triangle zone is missing and a number of Late Paleozoic grabens can be recognized, which were partly inverted by compression related to folding and thrusting of the Jura Mountains. For both cross sections the thrust faults in the Subalpine Molasse ultimately tie up with thrusts affecting the crystalline basement of the external massifs.

Seismic sections through the Alps is grouped into 4 chapters, each describing a network of lines covering a transect through a part of the Alps.

Chapter 9 consists of a network of near-vertical and wide-angle reflection, as well as refraction lines in eastern Switzerland. By combining these data a 3D-image of the top of the crystalline basement, a very important contact in conjunction with structural analysis, could be derived. Its shape contrasts with the much simpler shapes of the Conrad and Moho discontinuities and thus points to a detachment between the upper and lower crust in the course of the Cenozoic Alpine collision. Within the upper crust some of the peeled off basement flakes (Penninic thrust sheets) can be traced over a considerable distance along strike. Reflections from the upper crust are mainly generated at contacts, where lithologically different units are juxtaposed. Seismic modelling indicates that reflections often originate from off the line due to important cross dips, rendering migrations questionable.

A network of seismic lines covering the Southern Alps is discussed in **chapter 10.** The wedge of lower crust of the Adriatic plate which was forced into the European crust is seen to dip and thicken northwards. Within the upper crust the seismic data image a pile of nappes including crystalline basement and Mesozoic sediments. These nappes can be grouped from top to bottom into the Ivrea-Ceneri complex, the Orobic and the Lombardic nappe systems. They form an orogenic wedge which was thrust southwards.

The Central Traverse discussed in **chapter 11** traverses the entire Alps from the Molasse Basin to the Po Basin. It shows the Alps as a bivergent orogen with the S-dipping European lower crust subducted underneath the thickened N-dipping Adriatic lower crust. The seismic data show the European upper crust being stacked up to form the nappe pile of the Penninic basement nappes and the allochthonous Aar massif. In the Southalpine domain the crustal stack involves lower (Ivrea) and upper Adriatic crust.

Chapter 12 deals with a network of seismic lines located in the western Swiss Alps. These lines show the shortened NW flank of the external massifs and their back-folded SE flank. They also suggest the continuation of the Rhone-Simplon dextral-extensional fault at depth. A short longitudinal line allows a glimpse at the crust/mantle boundary at the front of the Adriatic wedge.

The next part, entitled *Geologic structure and evolution of the Alps,* discusses the deep structure for larger scale areas and structures, and links it to the geologic evolution.

Chapter 13 deals with the basement uplift in the external zone of the Western and Central Alps. Section 13.1 documents the 3D geometry of these crustal scale uplifts in a series of cross sections which are constrained by seismic data. The evolution in time is outlined by careful analysis of local sequences of deformation phases and by a study of fission track data. The regional analysis shows that both, the internal structure of these external massifs, as well as the local kinematic sequence of deformation (and related uplift) change along strike. In section 13.2 the shape and depth of the top-basement contact in the axial depression between the Aar and Aiguilles Rouges/Mt. Blanc massifs were explored using gravity data. The analysis suggests the presence of a low-density body within the basement and the gravity data are compatible with the position of the top-basement contact as interpreted from seismic data.

The Mesozoic-Cenozoic evolution of the Penninic nappes along the eastern traverse is discussed in **chapter 14**. A two-stage rifting is held responsible for thinning the Briançonnais continental crust prior to convergence; both Briançonnais margins were of upper plate type but with opposite sense. Alpine collision expressed itself in a complex polyphase deformation. Eocene subduction and nappe imbrication with high-pressure metamorphism was followed by Oligocene post-nappe folding and exhumation. Miocene collision resulted in the final exhumation by bivergent thrusting on the Insubric line and in the Helvetic foreland.

In the Southern Alps, discussed in **chapter 15**, the geologic evolution included a phase of Late Paleozoic transtension, which was reactivated by Mesozoic extension in relation to the opening of the Hallstatt-Meliata ocean in the Triassic and the Piemont ocean in the Jurassic. In Late Cretaceous to Tertiary times the South-Alpine continental margin evolved into a fold-and-thrust belt, compression being largely N-S in the area studied.

The structural evolution of the western Swiss-Italian Alps is the topic of **chapter 16.** The Eoalpine events are related to the partial disappearance of a number of oceanic and continental fragments. During the Tertiary the deformation of the European crust migrated to the NW and resulted in a stack of basement fold-nappes. Back folding tilted the nappe contacts and eventually lead to generalized uplift and mountain building.

Chapter 17 explains the geodynamic evolution of the Western Alps in the framework of plate tectonics. Palinspastic reconstructions outline the importance of lateral movements. After a subduction phase which resulted in high-pressure / low-temperature metamorphism in some units, strike-slip movements are held responsible for their exhumation. The subsequent continental collision was associated with a phase of continental subduction, followed by two phases of back folding which are related to "oceanisation" in the Western Mediterranean.

The part *Dynamic Alps* deals with the younger history and present day activity of the Alps, and relies on research outside the scope of deep seismic profiling.

Chapter 18 deals with recent seismicity. In map view the seismicity correlates with the location of the minima of isostatic anomalies and the maxima of uplift rates. Within the Alps the earthquake foci are located in the upper crust, whereas in the North-Alpine foreland they occupy the entire crust. The dominant deformation processes are strike-slip and normal faulting with the maximum horizontal shortening oriented NW–SE.

Recent crustal movements and density distributions at depth are analyzed in **chapter 19**. The recent vertical movements are consistent with general wedge-shaped pattern of Alpine uplift, the maximum being located just south of the crest of the external basement uplifts (Aar massif). Lateral density variations within the uppermost layers in the Molasse basin strongly affect the regional gravity anomalies. Astrogeodetic measurements of the deflections from the vertical illustrate the presence of the Ivrea mantle body.

In **chapter 20** Alpine cooling and uplift is assessed from Rb-Sr, K-Ar and fission track analyses. Three main Alpine events are proposed. Rb-Sr and K-Ar data corresponding to high closing temperatures show Alpine ages in the high-grade Penninic zone only. Fission-track zircon and apatite ages (closing at around 200 – 240° and 100 –120°C, resp.) are particularly young along the Rhone valley, over the Simplon to the Ticino area. The youngest ages correlate with the maximum recent uplift rate in the Brig area.

The incision and backfilling of Alpine valleys is addressed in **chapter 21**. Most of the major valleys are significantly overdeepened, the bedrock surface at the valley bottom often being below sea level. The valleys draining to the north were overdeepened to as much as 500 m below sea level in the course of the Pleistocene glaciations. Backfilling started in the waning stages of the last glaciation and included sedimentation in lakes that developed beneath floating glaciers. In the case of valleys draining to the south a major fluviatile incision occurred during the desiccation of the Mediterranean during the Messinian. The low base level led to incisions as deep as 500 m below sea level.

The final part, *Lithospheric and crustal scale interpretation,* synthesizes the geophysical and geological data in the framework of large scale and plate tectonics.

Chapter 22 comprizes an integrated cross section along the Eastern Transect, stretching from the Molasse basin into the Po basin. The crustal structure is assessed from structural data, as well as seismic reflection and refraction data; its evolution in time is illustrated based on a series of palinspastic geologic cross-sections. The Alpine collision involved the subduction of lithospheric mantle and lower crust of the Eurasian Plate. The corresponding upper crust was detached, shortened and thickened on gently dipping north-directed detachments and steeply dipping south-directed detachments.

A three-dimensional crustal model is developed in **chapter 23** based on the network of deep crustal seismic profiles covering the Swiss Alps. A wedge of Adriatic upper mantle and lower crust is seen to penetrate into the European crust. The tip of this wedge parallels the arc of the Central and Western Alps. So does the trough defined by the detached upper crust stacked in a pile of Penninic basement nappes.

In **chapter 24** the crustal scale profiles are related to lithosphere scale considerations. Three high-velocity bodies beneath the Swiss Alps and the adjoining Po plain to the south are correlated with the European continental lithosphere and with detached slabs of the subducted Valais and Piemont ocean lithosphere. The complex shape of the Adriatic Moho is compared to gravimetric data. It reflects the structural inheritance from the previous rifting phases.

Finally, in **chapter 25** the deep structure of the Swiss Alps is discussed in the framework of the lithosphere-asthenosphere system. A cold, high-velocity "lithospheric root" reaching about 200 km into the mantle beneath the Swiss Alps can be derived from the study of phase velocity dispersion, and resulted from the continental collision. Geodynamic modelling of this high density lithospheric "block" produces maximum model uplift rates in the central part of the Alps and subsidence in the Po basin, which compares well with the observed data. Left-lateral displacements indicated by focal mechanisms are in accordance with a counter-clockwise rotation of the Adriatic microplate in the last stages of the continental collision.

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The Editors

1 Deep structure of the Swiss Alps: an introduction

P. Lehner, St. Mueller & R. Trümpy

Contents

1.1 Organisation and logistics

P. Lehner

Between 1986 and 1995 NRP 20 carried out a comprehensive research program of geophysical and geological projects to study the deep crustal structure of the Swiss Alps. Four major reflection seismic traverses were recorded with a total length of around 500 km. They were connected by two refraction lines parallel to the strike of the Alps. In addition 18 research projects were completed in related geoscience fields, such as geodesy, gravimetry, seismicity, isotope geochemistry and structural geology.

The eastern traverse of NRP 20 was planned to coincide with the Alpine segment of the EGT (European GeoTraverse) as part of an international effort to study the European lithosphere.

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Valuable close contacts were maintained with the following international groups and institutions:

- CROP Italia (Crosta Profonda)
- DEKORP (Deutsches Kontinentales Reflexionsseismik-Programm)
- ECORS (Etude de la Crôute Continentale et Océanique par Méthode Sismique), France
- COCORP (Consortium for Continental Reflection Profiling), Cornell University, Ithaca, NY, USA
- COCORP, University of Wyoming, Laramie, WY, USA
- EGT (European GeoTraverse)
- Lithoprobe, Canada

1.1.1 Time table

1983	Concept of the program submitted to the Swiss National Science Foundation by P. Fricker, St. Mueller, E. Niggli and R. Trümpy
1984	Appointment of the experts committee with Prof. E. Niggli as President
1985	Approval of the program and budget by the Swiss government
1986	Recording of the Eastern Traverse (E1, fan lines E7 – E9) and the EGT refraction profile
1987	Western Traverse (W1 to W4) and refraction profile ALP 87
1988	Southern Traverse (S1 to S7) and refraction profile ALP 88
1989	Rhône Valley profiles
1990	Western Traverse (W5) and Central Traverse (C1 to C3)
1991	Eastern Traverse (E2 and E3) and Jura Mountains transect (J1)
1992	Rhine Valley profiles
1995	Completion of the program

1.1.2 Organisation

The committee of experts:

President: Prof. E. Niggli, University of Bern

Prof. D. Bernoulli, Geological Institute, ETH, Zürich
Prof. D. Betz, Kontinentales Tiefbohrprogramm (KTB), Hannover
Prof. Ch. Caron, Institute of Geology, University of Fribourg
Prof. M. Delaloye, Dept. of Mineralogy, University of Geneva
Prof. A. Escher, Institute of Geology and Paleontology, University of Lausanne
Dr. P. Fricker, Secretary General of the Swiss National Science Foundation, presently of the European Science Foundation, Strasbourg
Prof. H. Laubscher, Institute of Geology and Paleontology, University of Basel
Prof. W. Nabholz, Institute of Geology, University of Bern
Prof. A. Pfiffner (as of 1991), Institute of Geology, University of Bern
Prof. J.P. Schaer, Institute of Geology, University of Neuchâtel
Prof. St. Schmid (as of 1991), Institute of Geology and Paleontology, University of Basel
Dr. Ch. Sprecher, NAGRA, Nationale Genossenschaft für die Lagerung radioaktiver Abfälle, Wettingen
Prof. R. Trümpy, Institute of Geology, ETH, Zürich
Dr. B. Wieland, Federal Office of Energy, Bern

Consultants:

Dr. P. Eckardt, MC Mineral Consult AG, Zürich
Dr. Ch. Emmenegger, Director of the Swiss National Hydrological and Geological Survey, Bern
Prof. A. Lamer, Ecole Nationale Supérieure du Pétrole et des Moteurs, Rueil-Malmaison, France
Prof. St. Mueller, Institute of Geophysics of the Federal Institute of Technology, ETH, Zürich
Mr. R.W. Schoop, Geological Institute of the Federal Institute of Technology, ETH, Zürich

Program management:

Dr. P. Lehner, program director, Richterswil
Mr. W. Frei, manager geophysics, Institute of Geophysics, ETH, Zürich
Dr. P. Heitzmann, manager geology, Swiss National Hydrological and Geological Survey, Bern
Mrs. H. Anderegg, secretary and accountant, Richterswil

Representative of the Research Council of the Swiss National Science Foundation:

Prof. F. Eggimann, Managing Director of Eidg. Materialprüfungsanstalt (EMPA), Dübendorf

Secretariat of the Swiss National Science Foundation (NF):

Dr. B. Butz, NF Bern

Traverse coordinators:

Eastern Traverse: Prof. A. Pfiffner
Central Traverse: Prof. A. Pfiffner, Dr. P. Heitzmann
Southern Traverse: Prof. D. Bernoulli, Dr. P. Heitzmann, Dr. A. Zingg
Western Traverse: Prof. A. Steck, Prof. A. Escher

Geophysical working groups:

Swiss Working Group of Deep Seismic Profiling, Federal Institute of Technology (ETH) Zürich. Members:
J. Ansorge, St. De Haas, P. Finckh, R. Freeman, W. Frei, A. Green, L. Hitz, K. Holliger, H. Horstmeyer, L. Jemmi, E. Lanz, P. Lehner, St. Mueller, A. Pfiffner, S. P. Smithson, M. Stäuble, P. Valasek

The main responsibility of this group was the planning and supervision of the field surveys and the data processing at the Institute of Geophysics, ETH

Zürich. The facilities used were SSL's PHOENIX seismic processing system and a SIERRA seismic modelling work station.

GRANSIR (Groupe de Recherche et d'Analyse Numérique de Sismique de Réflexion) Universities of Lausanne and Geneva, coordinated by Prof. R. Olivier, Institute of Geophysics, University of Lausanne and Prof. J. J. Wagner, Dept. of Mineralogy, University of Geneva. Members:

D. Alioth, S. Besnard, P. F. Erard, L. Levato, R. Marchant, R. Olivier, M. Ouwehand, B. Pruniaux, S. Sellami, H. Stampfli, J. J. Wagner

GRANSIR was responsible for the data processing at the EPFL (Ecole Polytechnique Fédérale de Lausanne) computer centre featuring CGG's GEOVECTEUR processing system on a CRAY supercomputer. They also had at their disposition a CHARISMA work station at the Institute of Geology and Paleontology, University of Lausanne.

Satellite projects of NRP 20:

In addition to the seismics surveys the following research projects were completed:

- Seismic refraction profiling: Two profiles with dense station spacing, parallel to the Alpine strike. J. Ansorge, K. Holliger, S. Ye.
- Seismicity: Earthquake recordings with a network of portable stations over a period of 2 years in the Eastern and Western Alps. N. Pavoni, Ph. Roth, H. R. Maurer.
- Isotope geochemistry: Radiometric age determination and fission track measurements, mainly to determine the long-range uplift and cooling history of the Alps. J. Hunziker, A. J. Hurford, L. Calmbach.
- Geodesy: High precision levelling and GPS measurements (Global Positioning System). H. G. Kahle, E. Gubler, U. Marti, A. Geiger, B. Wirth, M. Rothbacher, W. Gurtner, G. Beutler, I. Bauersima.
- Petrophysics: Laboratory measurements of sound velocity, density and magnetic conditions. J. J. Wagner, F. Barblan, S. Sellami, A.-M. Mayerat.
- Gravimetry: Ground-based survey along the Western Traverse. R. Olivier.
- Gravimetry: Two-dimensional gravimetric study, Rawil. E. Klingelé.
- Geodynamic modelling of Alpine uplift and cooling. D. Werner, N. Okaya.
- Rawil Depression: A. Steck, J. Ramsay, D. Dietrich, R. Herb†/A. Pfiffner, H. Masson, E. Klingelé.
- Penninic zone, Western Alps: A. Steck, A. Escher, H. Masson.
- Penninic basement nappes, Eastern Switzerland: A. Pfiffner, A.-M. Mayerat, E. Klaper.
- Penninic cover nappes, Eastern Switzerland: St. Schmid, Ph. Rück, G. Schreurs.
- Alpine root zone: P. Heitzmann.
- Southern Alps: D. Bernoulli, G. Bertotti, M. Schumacher, G. Schönborn, A. Zingg.
- Neotectonics, Eastern Switzerland: P. Haldimann.
- Jura Neuchâtelois: M. Burkhard, A. Sommaruga.
- The deep structure of the Basel Jura: H. Laubscher, T. Noack.
- Eastern Jura, influence of Variscan structures on Tertiary tectonics: P. Diebold
- Reprocessing of industry lines across the Swiss Molasse Basin: A. Pfiffner, M. Stäuble (eastern Switzerland E4 – E6), R. Olivier, P.-F. Erard, A. Pfiffner (western Switzerland W7 – W10).

1.2 The special case of Alpine seismic reflection profiling

P. Lehner

The seismic reflection surveys of NRP 20 in the Swiss Alps and by ECORS and CROP in the Western Alps of France and Italy began in 1986. These surveys were the first attempt to use stacked, near-vertical reflection seismics to study the deep crustal structure of the Alps. It was also the first time this technique was used to obtain continuous regional transects across an active continental collision zone.

The application of near-vertical seismic reflections for crustal studies actually began in the late seventies, to complement conventional refraction and wide-angle reflection techniques. With their first regional profile across the Windriver Range in the Wyoming Rocky Mountains (USA) in 1976–1977, COCORP (Consortium for Continental Reflection Profiling) demonstrated that the near-vertical reflection method could yield valuable new information about the internal structure of the earth's crust, down to the Moho. The European seismic reflection program began in 1983 as part of the European Geotraverse. The first Alpine traverse was recorded in September 1986 by NRP 20. The seismic reflection method was developed by the petroleum industry for the search of hydrocarbons. To make use of such highly specialized industry techniques for scientific purposes takes considerable courage, not only because of the novelty of the approach but also because of the costs, which are usually way beyond the reach of academic institutions.

During the planning stage of the NRP 20 the applicability of seismic reflections for mapping crustal structures in the Alps was questioned by the consulted experts from the petroleum industry. They feared that the intensely folded Alpine structures would not be detectable with seismic reflections and that there was not sufficient acoustic impedance contrast between the different metamorphic rocks of the Alpine basement to produce reflections. These doubts were based on the past experience of the petroleum industry, which developed the seismic reflection method for the exploration of hydrocarbons in sedimentary basins with moderate tectonic disturbances and high impedance contrasts.

The first use of the seismic reflection method for subsurface mapping of petroleum prospects dates back to the mid-twenties. Its real development began only some 30 years later, with the arrival of modern computers. A major breakthrough was the introduction of impedance seismics in the late sixties which made it possible to produce true amplitude synthetic seismograms from velocity and density measurements in boreholes. With this method a direct link between the seismic field records and the subsurface lithology, including the pore fill ("bright spot") was established. In basins with sufficient calibration points from boreholes, even oil and gas accumulations could be identified on seismic records. Instead of tracing "phantom horizons", individual formation boundaries could be mapped with confidence. The success of seismic stratigraphy is a direct result of this remarkable development.

Tectonically disturbed regions with steep dips and numerous faults nevertheless remained a major problem. With modern 3-D (three-dimensional seismic methods), introduced in the early eighties for detailed structural mapping of potential oil fields, this hurdle was also overcome. The cost of 3-D surveys, which require a dense observation grid, resulting in an enormous volume of data, are still prohibitive for regional surveys.

The results of the NRP 20 Alpine campaigns turned out to be far better than expected, but even so, Alpine profiles look somewhat chaotic compared to standard seismic sections in sedimentary basins. There is an obvious reason for this. Sedimentary sequences tend to be well-layered, with relatively flat and smooth beds extending over large areas. The Alpine experiment, however, intended to explore the deep crustal structure. Its main target was the internal structure of the basement, composed of intensely deformed and metamorphosed magmatic rocks and metasediments. Even in the two sedimentary basins flanking the Alps, the Molasse basin to the north and the Po basin to the south, the sediment cover occupies only a small portion of the profiles.

Based on an extensive network of seismic refraction profiles the thickness of the crust below the Alps and its internal velocity structure were known in broad outlines at the beginning of the program. The data showed that the Moho, which in the northern and southern foreland of the Alps is observed at a depth of around 35 km, plunges to a depth of more than 50 km below the Alps. The recording parameters of the reflection seismic program (the spacing of source and recording stations and the strength and length of the signal) therefore had to be geared for great depth penetration, with the unavoidable consequence of a loss of information at shallow depths, particularly in the upper 1 to 2 seconds TWT.

The geological interpretation of seismic reflection sections is often thought to be an art rather than a science – experience and intuition being more important than numerical analysis. This is certainly not the case in areas with a dense seismic grid and sufficient well control. The NRP 20 seismic project, however, consists of individual reconnaissance lines, most of them tens of kilometers apart, without connecting crosslines. Only two profiles are strike lines, namely E2 in the Eastern Alps and W4 in the Western Alps. To improve the regional coverage some 30 short profiles (5 – 10 km long) were recorded between the main traverses.

The shortcoming of single, disconnected traverses for structural mapping is obvious. With a single, linear array of receivers and shotpoints it is not possible to discriminate against crossdip. Without sufficient 3-D information even the value of migrated profiles is open to questions. To obtain true 3-D information a recording grid is required with a density adjusted to the size and depth of the objectives. Under Alpine conditions this would be prohibitively expensive.

The simple crossing of the Alps alone has been a problem since prehistoric time, to think of Ötzi, Hannibal or Caesar. Seismic traverses have an additional disadvantage because the traditional Alpine passes, crowded with highways, railroads, powerlines and pipelines, represent the worst conditions for seismic recording.

Without deep well control within the Swiss Alps proper, between the Molasse basin to the north and the Po basin in the south, velocity information and the related depth control of the seismic profiles is based on refraction surveys only.

This lack of well control is compensated in a way by the excellent outcrop conditions and the availability of detailed geological maps and profiles. The axial culminations of the Alpine chain not only provide exposures of deep tectonic levels of the Alpine edifice but also make it possible to project surface structures along their plunging axis to great depth into the axial depressions. This method presumes, of course, a certain cylindricity in the gross structural grain of the Alps. Based on such projections it is possible, for instance, to demonstrate that the gneiss cores of the nappes appear as more or less transparent intervals between the layered metasediments or mylonite belts.

Even in zones of high reflectivity, in the upper 8 sec TWT of the Penninic zone in the eastern and western traverses, respectively, individual reflections can rarely be traced continuously over distances of more than a few kms. What can be traced with confidence over distances of 10 to 20 kms are broad bundles of wavelets (250 to 100 ms wide). This method commonly used for the interpretation of crustal profiles amounts actually to the outlining of envelopes of reflective intervals bounded by more or less transparent zones.

When judging the value or correctness of the interpretation of these regional profiles it is helpful to consider two different aspects or steps of the interpretation independently:

The first step is the geophysical interpretation of the stacked and, if possible, migrated profiles in terms of acoustic imaging. "Obvious" reflections are identified and labelled without geological connotation. The criteria are strictly acoustic, whereby the different steps in the processing sequence are taken into consideration.

The second step is a geological interpretation in terms of rock units and structure. At this stage, independent considerations from outside sources enter the field and may even dominate the in-situ recorded seismic data. Examples of such outside data include the projection of potential reflectors into the seismic profile, the expected structural style extrapolated from adjacent regions or inferred from analogues, and extrapolated nappe contacts. For the crustal-scale interpretation, refraction data or gravimetry may become of critical importance.

In the absence of synthetic seismograms from well logs and without sufficient 3-D coverage both interpretations remain subjective to a certain degree, depending on the validity of the accepted models and the mood of the interpreter. The two aspects may also not be as independent as suggested here. It is conceivable, for instance, that a rather poor profile can be interpreted with confidence because of an obvious geological situation or on the other hand an excellent profile could be interpreted in several ways because of conflicting models.

The Alpine seismic experiment of NRP 20 posed the challenge of a pioneering venture with the inherent excitement of entering new, uncharted territory, which may contain the answers to some of fundamental problems of Alpine geology or even collision tectonics in general. With this Atlas, which contains the raw geophysical data as well a the geological interpretations, we hope to keep this pioneering spirit alive and encourage new and innovative thinking about the structure and the origin of the Alps or similar collision orogens.

1.3 Geological problems addressed by NRP 20

R. Trümpy, P. Lehner

1.3.1 General remarks

The National Research Program 20 (NRP 20) intended to explore the deep structure of Switzerland and its bearing on practical problems of our society. At the onset of the program, in 1984, the experts committee formulated a number of questions relating to geological structures at shallow and intermediate depth. These questions were subsequently modified according to preliminary results and according to new problems arising. One of the topics added to the program consisted in exploring the very shallow subsurface structure of some of the Alpine valleys. The seismic reflection studies in the frame of NRP 20 were thus aimed at problems at the following three scales:

- Supracrustal structures down to depths of about 10–15 km involving essentially the upper crust, late Paleozoic sediments and volcanics, as well as Mesozoic-Cenozoic sediments and ophiolites. These structures can be correlated with structures observed on the surface and, in the Molasse Basin and south of the Alps, also with the results from a few boreholes.
- Deep crustal (and eventually lithospheric) structures, beyond about 10 km depth, generally not covered by industry surveys. The seismic reflection data can be correlated with those of seismic refraction surveys, gravimetry and other geophysical methods.
- Very shallow structures related to the shape and Quaternary fill of Alpine valleys (some hundreds of m deep), which, in addition to their scientific interest, were investigated in consideration of their practical importance.

Structural units of the Alps and their foreland

We presume that the reader is familiar with the general tectonics of Switzerland (Figure 1-1).

European elements are the Tabular and Folded Jura, the Molasse Basin, the external basement massifs, the Helvetic nappes s.l. and the lower Penninic units. The Subpenninic or Infrapenninic complex (Gotthard "massif" and lowest nappes in the Ticino-Simplon transversal culmination) constitutes a link between the Penninic and Helvetic domains.

The Penninic basement and cover nappes are derived from the Jurassic-Cretaceous oceans, with parts of their margins and with intra-oceanic continental slivers. Ophiolites are restricted to the Penninic domain.

The Ultrapenninic units (Dent Blanche – Sesia, i. e. the so-called Austroalpine of the Western Alps, and Margna to the east) occupy an intermediate position between Austroalpine and Penninic domains.

The Austroalpine nappes and the Southern Alps formed the northern and western margin of the Adriatic (Apulian) plate. The Southern Alps, with predominant south-facing structures, are bounded to the north by the great Insubric fault.

Geological evolution of the Alpine orogen

The Alps are the product of a complex evolution. The Variscan and pre-Variscan basement complex does not seem to differ, in a significant manner, from its equivalents in surrounding regions. The grade of Variscan metamorphism and the intensity of Variscan deformation decrease, in a general but not systematic way, towards the SE. Carboniferous and (subordinately) Permian granitoids are abundant in the external massifs, in the Infrapenninic complex and in some Middle Penninic and Lower Austroalpine nappes. Late Carboniferous and Early Permian graben-like structures, with terrestrial sediments and calcalkaline followed by bimodal volcanics, occur in all tectonic belts of Switzerland. Widespread Triassic shallow-water sedimentation indicates a fairly stable crust, of presumably normal thickness, although several km of carbonate rocks accumulated in the southern and eastern parts. The eastern Meliata-Hallstatt oceanic tongue does not reach so far to the W.

A phase of pre-oceanic rifting along normal, frequently listric faults began in earliest Jurassic (in the SE, late Triassic) time and lasted into the Middle Jurassic. Especially in the future Penninic and Austroalpine-Southalpine realms, it led to stretching and thinning of the continental crust. Where the paleotectonic structures can be assessed, the stretching factor remains fairly modest (around 1.2). This does not exclude that more pronounced stretching, by low-angle normal faults, may have occurred, in areas too strongly deformed to allow reconstruction. Many rifts are oriented SSW-NNE.

The oceanic stage of the Alps started in mid-Jurassic time, simultaneously with the first oceanic opening of the Atlantic. The existence of a somewhat older (late Early Jurassic), Red Sea-type opening cannot be excluded. The north-Penninic (Valais) trough is apparently younger, essentially Cretaceous, than the south-Penninic (Piemont) one. In addition to spreading, considerable lateral displacement is involved; some parts of the small oceans may have had the character of transtensional rhombochasms or pull-apart basins. The Alpine ophiolite sequences are thin and incomplete. Tectonic denudation of peridotitic ocean floor by asymmetric simple shear is invoked by several authors (e. g. Lemoine, 1986; Trommsdorff, 1992; Stampfli & Marchant, this volume).

The eo-Alpine deformations set in during the Early Cretaceous and reached their climax in early Late Cretaceous time. The internal structure of the Austroalpine and Ultrapenninic nappes dates from this period. E to W movements are conspicuous in the Austroalpines. Penninic and Ultrapenninic units were subducted beneath the Apulian rim and underwent high-pressure metamorphism of blueschist type, often preceded by the formation of eclogites. The intra-Penninic Briançonnais rise was apparently spared from the Cretaceous deformation. Cretaceous events in the north-Penninic (Valais) trough are probable but not yet well understood; in the central part of the Valais basin, Cretaceous sedimentation was fairly continuous. The eo-Alpine orogeny was certainly complex, involving (earlier ?) lateral displacements as well as subduction and, in the Eastern Alps, incipient collision.

A relative lull ("Paleocene restoration") seems to have intervened between the eo-Alpine and the meso-Alpine deformations.

The meso-Alpine movements (late Paleocene-early Oligocene) affected all the Penninic nappes and account for the north-directed overthrust of the Austroalpine nappes. Some Penninic nappes show high-pressure metamorphism of this age. Stratigraphical data suggest a Late Eocene climax.

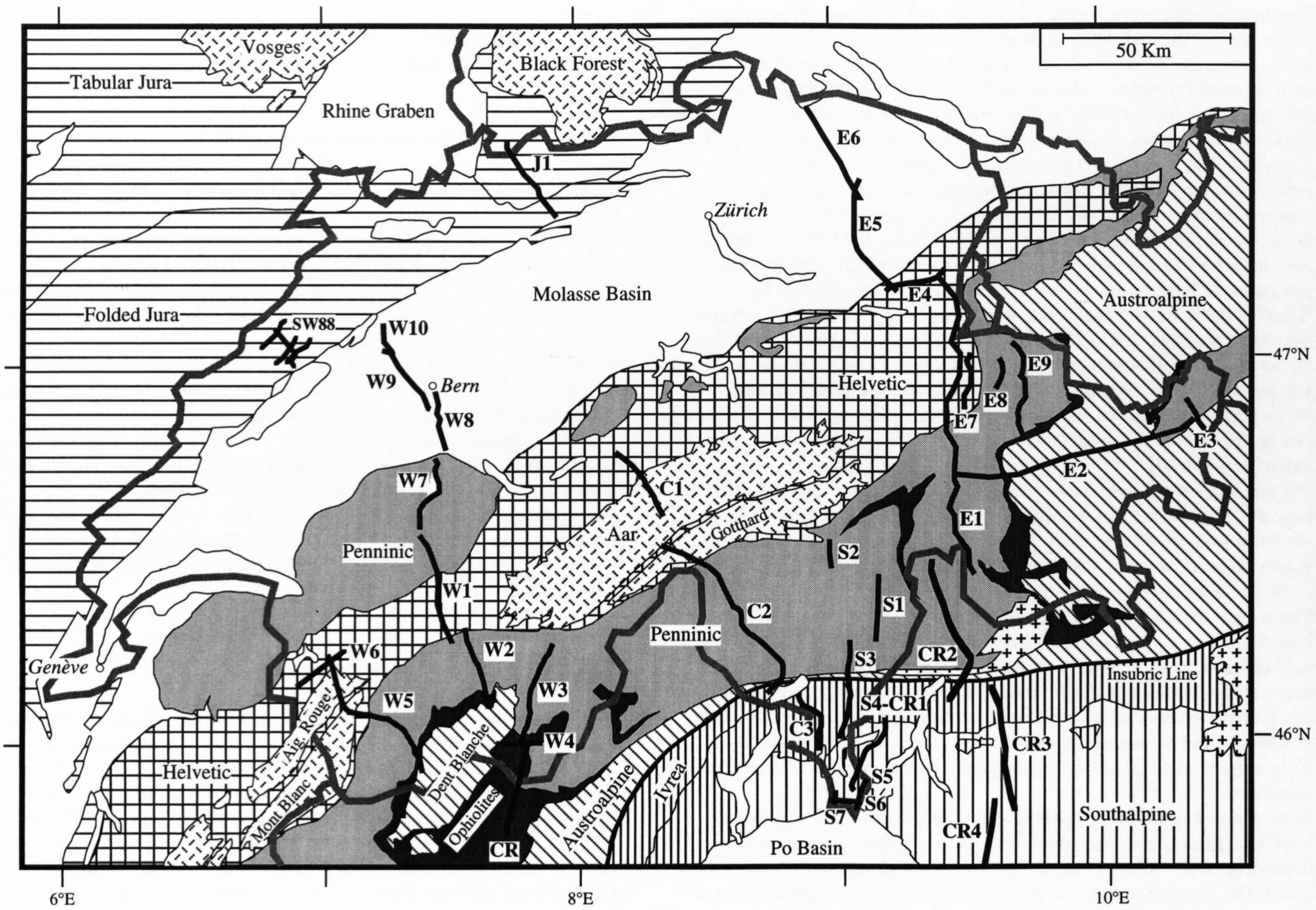

Figure 1-1
Regional tectonic map of Switzerland with the traces of NRP 20 seismic reflection lines.

Radiometric data, on the other hand, indicate a thermal peak around 38 Ma, which is "too early", considering the slow speed of heat transfer. This contradiction may suggest that movements started well back in the Eocene or even in the Paleocene. There is no systematic break between the meso-Alpine and the neo-Alpine (Late Oligocene and Neogene) movements. Several important events occurred during the Oligocene: a change of the stress field from S-N to SE-NW compression (in the W), the initiation (?) of displacements along the Insubric faults, the emplacement of the Bregaglia granitoids, the first major uplift of the Alps and the acceleration of subsidence in the Molasse Basin.

In the course of the **neo-Alpine deformations**, the Jura, the Helvetic nappes and the external massifs were added on the European side and the southern part of the Southern Alps on the Adriatic side. Many of these features may be related to the impact of the "Adriatic indenter", which reflects a fairly late event.

These general remarks call for two warnings against a simplistic interpretation of seismic sections.

The structures detected by reflection seismics are, to a large extent, determined by the neo-Alpine deformations, which may well have obliterated or at least modified older, meso-Alpine and eo-Alpine structures.

The Jura, the Helvetic zone (Ultrahelvetics excluded) and the Southern Alps are fairly coherent (in the sense of Trümpy, 1969) and allow the construction of balanced cross-sections. In the Penninic and Austroalpine nappes, on the other hand, we have to consider large lateral displacements, expecially of Late Jurassic, Cretaceous and Oligocene age. The presence of "terranes" in the internal zones of the Alps is indeed probable (see e. g. Stampfli, 1993), even if these fragments are small and have not very fartravelled. "Geotraverses" may juxtapose elements of originally quite different position.

1.3.2 Supracrustal structures

As already stated, structures down to a depth of around 10 km (or more, where axial down-plunge projection of surface feature allows) will be discussed under this heading. A number of relatively precise questions related to these supracrustal structures were initially formulated by the experts committee and may be recalled here:

The questions related to the Jura Mountains and the Molasse Basin that NRP 20 addressed initially concerned a possible relation between Late Neogene Jura folds and older structures (including Late Paleozoic troughs and Oligocene-Miocene faulting and warping), as well as the southward continuation of the thrust faults of the Subalpine Molasse. Within the Alps NRP 20 intended to explore the link between the external basement uplifts in the Helvetic zone and the crystalline basement underlying the Molasse Basin and the subsurface continuation of some of the major Alpine thrust faults. Of particular interest were the basal thrusts of the Helvetic and Prealpine nappes in front of the external basement uplifts, and the basal thrust of the Penninic nappes south of these uplifts. Another question concerned the upper crustal structure beneath the Penninic nappes: would the thrust faults separating individual thrust sheets which consist of crystalline basement be imaged by seismic reflection profiling and confirm projection techniques such as those put forward by Argand? Also the surbsurface continuation of major structures, such as the ophiolite-bearing sutures, the Tertiary granitoid bodies and the dense Ivrea body were recognized as topics of primary interest. In the Southern Alps it was hoped to find out how far crystalline basement rocks are involved in the nappe pile observed at the surface.

Beyond our expectations, NRP 20 has furnished data which will answer, at least partially and with varying degrees of confidence, most of these questions.

Jura and Molasse Basin

The Swiss Molasse Basin is covered by a reconnaissance grid of reflection seismics, with dip-lines approximately 10 km and connecting strike-lines 20 to 30 km apart. These surveys were carried out for the purpose of hydrocarbon exploration by the petroleum industry and, since 1982, by NAGRA, for the search of possible nuclear waste disposal sites. The petroleum industry in addition has drilled some 30 deep wells in the basin, resulting only in one minor commercial gas discovery from Mesozoic carbonates.

In order to save the NRP 20 funds for profiling in the Alps, it was decided to rely on the exchange of industry data for the Molasse Basin and the Jura Mountains. The exchange coverage in the foreland consists of two transects across the Molasse Basin as the northern extensions of the Eastern Traverse

(E4 – E6) and of the Western Traverse (W7 – W10), one profile (SW 88) with crosslines across the western Jura Mountains, one crossline (W6) at the NW end of the Western Traverse (W5) and two profiles in central Switzerland at the northern end of the Central Traverse (C1).

The quality of seismic records in the foreland is good to fair. The fluvio-deltaic environment of the Tertiary (Oligocene and Miocene) basin fill creates unfavourable conditions, as seismic velocities may vary rapidly and erratically. Within the Molasse supergroup, only the base of the thick-bedded sandstones in the OMM (Upper Marine Molasse) produces a continuous reflection in the eastern half of Switzerland.

The Mesozoic sequence underneath the Molasse, consisting mainly of carbonate rocks, was the principal object for hydrocarbon exploration during the last decades. It appears as a conspicuous band of reflections, about 0.5 sec TWT wide in the N and W, about 0.25 sec in the SE. The corresponding thickness in boreholes along the Alpine front is around 1000 m or slightly less. The top of the Mesozoic carbonates (Upper Jurassic in the E, Cretaceous in the W) is usually marked by a strong reflection. Lower markers can be matched with the top of Middle Jurassic, locally also Lower Jurassic limestones. A strong, often two-fold reflection is produced by the Middle Triassic (Muschelkalk) carbonates and anhydrites. The Lower Triassic Buntsandstein is absent from most of the Molasse Basin. Still deeper, inclined, truncated and often rather indistinct reflectors can be assigned to Upper Carboniferous and Permian detrital formations. The existence of such late Variscan basins has been confirmed by the Entlebuch borehole, near the front of the Alps, and by the NAGRA boreholes in the northern part of the Molasse Basin.

The quality of reflections from the Mesozoic sediments deteriorates below the external Alpine overthrusts, but they can still be clearly recognized below the Helvetic nappes and even below the front of the external basement massifs.

As expected, the Mesozoic formations dip gently towards the S or SE, attaining a maximum depth (about 7 km) beneath the Helvetic and Prealpine nappes. Some faults, offsetting the Mesozoic carbonates but not always the younger groups of the Molasse, can be seen or inferred on both western and eastern traverses.

The direction, nature, throw and age of these faults have considerable bearing on the mechanism of the Jura folding. According to Buxtorf (1907) the basement and its tegument (Buntsandstein and Lower Muschelkalk) were not directly involved in the Jura folds. Laubscher (1961) formulated the famous Fernschubhypothese (far-thrust hypothesis), according to which the entire Jura and, eo ipso, the Molasse Basin had been displaced, along the anhydrite (and, locally, halite) bearing detachment level of the Middle Muschelkalk (review in Jordan, 1992). Pfiffner et al. (Chapter 8) discuss the architecture of the Molasse Basin and question the feasibility of such a general detachment along the Triassic evaporites. The basement below the Jura is certainly not a simple, undisturbed slab. The Late Miocene, eventually also Early Pliocene Jura folding was influenced by discontinuities such as the Permo-Carboniferous graben structures, Oligocene to Early Miocene faults related to the Rhine graben system and Miocene, pre-thrust warping (Diebold & Laubscher, Chapter 7.2). The local study by Sommaruga & Burkhard (Chapter 7.1) testifies to the excellent quality of modern industrial seismics within the Jura.

Helvetic and Penninic cover nappes

The Prealpine nappes of western Switzerland, the Helvetic nappes of central and eastern Switzerland as well as the Calcareous Alps in front of the Eastern Alps occupy the internal, proximal part of the Molasse Basin, from which the sheets of the Subalpine Molasse have been expelled.

The base of the Helvetic nappes is recognizable by discontinuous reflections, due to the velocity contrast between the underlying flysch and molasse rocks and the overlying Mesozoic carbonates. A band of strong reflections follows the base of the Penninic nappes in the Prealps; it is probably caused by Triassic anhydrites. The internal structures of both nappe complexes are too shallow, too complicated and often too steep to be detectable with near-vertical reflection seismics.

The external basement massifs

These great wedges of European pre-Triassic basement rocks are characteristic of the Western and Central Alps. They are absent from the Eastern Alps and from most of the Carpathians; analogues in other mountain belts are also rather rare.

In Switzerland, the external massifs are represented by the Aiguilles Rouges and Mont Blanc massifs to the SW, the Aar massif with its northern offshoot, the Gastern massifs to the east (see Escher et al., Pfiffner et al., Steck et al., Chapters 16, 13.1 and 12). The Aiguilles Rouges – Mont Blanc and the Gastern – Aar couples are offset by an E-W trending dextral displacement, which does not appear at the surface. The more southerly Tavetsch and Gotthard "massifs" are clearly allochthonous and will be briefly discussed under the next heading.

Below the massifs, seismically transparent upper crust, consisting presumably of basement rocks deformed by steep Variscan and Alpine structures, reaches an anomalous thickness of 40 to 45 km. This accumulation of upper crust can theoretically be explained in two ways: either by ductile shortening and thickening at great depth, or by a tectonic duplication of the basement along S-dipping thrusts.

The reflection seismic data of NRP 20 have provided a partial answer to this question. Vollmayr (1987) had already shown that in central Switzerland the autochthonous sediments could be followed for a considerable distance below the front of the Aar massif. In front of the Aiguilles Rouges massif, Steck et al. (Chapter 12) postulate the existence of two deep, subhorizontal wedges of Mesozoic sediments separated by basement rocks. Pfiffner et al. (Chapter 13.1) interpret the same data as indications of a more moderate imbrication. At any rate, it is fairly certain that the Aiguilles Rouges massif, the "most autochthonous" of the Swiss massifs, is overthrust into its foreland.

On the contrary, the traverse through eastern Switzerland has failed to reveal the existence of a major thrust below the eastern part of the Aar massif (Pfiffner et al., Chapters 9 and 13.1). Minor imbrications of sediments and basement rocks along the northern slope of the massif do indeed seem probable, but on the whole this easternmost massif appears to be "more autochthonous" than its western counterparts. It is significant that Jura folds do not exist along this traverse.

The Helvetic-Penninic boundary belt

The Helvetic-Penninic boundary is indistinct and has never been properly defined. This applies both to the crustal distinction ("normal" European continental crust vs. thinned crust with oceanic stretches) and to the paleogeographical distinction (European shelf vs. North-Penninic Valais trough). The sharp outcrop boundary in the Western Alps is due to displacements along later tectonic planes, i.a. the "chevauchement pennique frontal", which cut out the transitional zones.

This transitional belt is only exposed in the transversal uplift of central Switzerland. Here, the Subpenninic complex of Milnes, 1980 (which we prefer to call Infrapenninic) comprises the Gotthard "massif" to the N (considered as "Helvetic" in most of the following papers) and the lowest gneiss nappes (Lucomagno – Leventina, Verampio, possibly also Simano to the E, Antigorio to the W; the higher "gneisses of the Lebendun nappe" are probably Mesozoic metaconglomerates). The Mesozoic (Triassic to Middle Jurassic), partly detached cover of the Gotthard and Lucomagno is still of Helvetic, more specifically Ultrahelvetic type. The passage to North-Penninic development of the Mesozoic can lie anywhere in the more internal Infrapenninic units; at any rate, Adula in the E and Monte Leone in the W may be considered as "true" Penninic nappes.

In the N, the structures of the Gotthard "massif" are steep, and thus hardly decipherable by reflection seismics. The still more northerly Tavetsch massif crops out in the upper Rhine valley. Its basement rocks are considered to represent part of the substratum of the Helvetic nappes. Whether the Piora sediments, between the Gotthard and the Lepontine gneiss nappes, are a fairly simple S-facing synform or a major nappe boundary is in discussion; a pilote gallery has encountered Piora sediments at a deep level (March 1996). The main part of the Infrapenninic elements consist of fairly flat-lying gneiss nappes, affected by intense ductile deformation. These contacts were imaged by the seismic lines of the Central Traverse (Pfiffner & Heitzmann, Chapter 11). Tertiary metamorphism reaches the high amphibolite grade, so that in the center of the late-Alpine Lepontine dome, the Oligocene overburden can be estimated at some 25 or even 30 km above the present surface. The present European Moho lies almost 60 km below the surface. This great stacking of crust implies major detachments, possibly between lower and upper crust. The Infrapenninic and lower Penninic basement nappes are mainly formed by upper crustal rocks, including abundant Variscan metagranitoids; some slivers of ultramafic rocks, such as the famous garnet peridotites of Alpe Arami, may represent shards of subcrustal mantle. Toward the S, the nappes bend around into the steep position of the "root zone".

In Valais W of Brig and in the entire Western Alps, the Infrapenninic and lower Penninic basement nappes do not reach the surface, except for tiny slices. Only sediments and rare ophiolites from this belt are exposed in the Sion – Courmayeur zone and in some cover nappes (Niesen etc.) of the Prealps. The gneiss nappes are cut by the Late Miocene Simplon accident (Mancktelow, 1990; Steck, 1987), a dextral and normal down-to-the-SW fault, which continues into the Rhone valley and presumably links up with the "chevauchement pennique frontal" of the Western Alps. The Simplon fault itself does not appear as a continuous band of reflections, in spite of the conspicuous mylonites along its outcrop. Its presence can be deduced from the angular cutoff of reflectors in the footwall and in the hanging wall (Steck et al., Chapter 12). Deep reflections below and to the S of the Simplon – Rhone fault can be attributed to Infrapenninic and lower Penninic basement-involving nappes. It is, of course, highly conjectural to correlate individual reflectors with presumed nappe boundaries.

One of the surprises in the western transects was the presence of fairly distinct N- to NW-dipping reflectors near the inner margin of the external massifs. It is true that structures with N-dipping axial planes have been known for a long time (Italian side of the Mont Blanc massif; Piora synform between the Infrapenninic Gotthard and Lucomagno basement bodies; Berisal synform in the Penninic nappes of the upper Valais), but the extent of this phenomenon had been underrated by most authors. The Eastern Traverse did not furnish indications for such great "backfolds". They seem to be characteristic for the Western Alps and for the western part of the Central Alps, and may well be linked to the much stronger incidence of the Adriatic wedge in the southwestern half of the chain (see Stampfli & Marchant, Chapter 17).

The eastern continuation of the Infrahelvetic and Lower Penninic nappes is uncertain. Here as well, the existence of a young normal – sinistral fault, hidden beneath the alluvium of the Rhine valley, may be suspected (e. g. Trümpy, 1992), but not proven. Pfiffner & Hitz (Chapter 9) plausibly assign reflections at 10–12 km depth, below the Engadine window, to the footwall of the Adula nappe, and thus to the base of the Penninic nappes s. str. It will be interesting to follow these reflectors eastwards and to find out whether they tie up, in one way or another, with the gneiss nappes exposed in the Tauern window.

Penninic, Ultrapenninic and Austroalpine nappes

In both transects across the main body of the Penninic nappes, the portion of the crust down to 6 or 7 sec TWT (almost 20 km) appears well-layered, with numerous distinct reflections. These reflectors have originally been attributed to mylonite zones in the footwall of basement nappes, but most of them seem to mirror the velocity contrasts between basement gneisses and Mesozoic metapelites (Bündnerschiefer etc.) on the "slow" side, ophiolites as well as Triassic dolomites and anhydrites on the "fast" one.

In 1911, Emile Argand introduced the method of oblique projections along the axial plunge of nappes, allowing the construction of profiles down to depths of about 20 km below the surface. The reflection seismics of NRP 20 provided a test for this hypothesis, which had often been criticized and branded as "cylindristic". It may be said that the validity of Argand's method has been fully confirmed. Many strong reflections occur just where major lithological discontinuities should be expected, so that they can be correlated, with a good to fair degree of confidence, with the tops or bottoms of individual basement nappes known from the excellent outcrops. Argand's method fails only where late normal-transcurrent faults, such as the Simplon or the Engadine lines, intervene.

For the detailed geological interpretation of the seismic section, we may refer to the contributions of Steck et al. (Chapter 12), Pfiffner & Heitzmann (Chapter 11) and Pfiffner & Hitz (Chapter 9). Of course, many problems remain unsolved in this complex belt of the Alps. The paper by Schmid et al. (Chapter 14) marks an important step towards the solution of one of trickiest, concerning the origin of the Schams nappes. In the eastern traverse, an internal, supra-Suretta, ophiolite-involving subduction scar (Platta and Avers ophiolites) can be clearly distinguished from a lower, supra-Adula one (Chiavenna and Vals ophiolites). It could be assumed that the first mirrors Cretaceous, the second Tertiary subduction. In the west, the position of some ophiolites, such as Antrona, remains open. The Austroalpine nappes have been only touched marginally by the NRP 20 profiles, where the base of the Silvretta basement nappe (or the underlying ophiolites) can be discerned.

The aggregate thickness of the Penninic nappes may attain about 20 km. Individual nappes are rather thin, a few km to a maximum of 12 km. The original (Triassic) continental crust was apparently of normal thickness (around 30 km in the northern and southern foreland of the Alps). The Jurassic rifting alone does not suffice to explain the thinning of the crust; stratigraphical data indicate a rather modest stretching. Furthermore, the basement of the Penninic nappes s.str. (but not of the Ultrapenninic nappes) consists almost exclusively of upper crustal type rocks. We have to consider important detachments, possibly somewhere near the top of the lower crust or even at shallower levels.

The entire pile of Penninic, Ultrapenninic and Austroalpine nappes narrows downwards and is wedged between the S-dipping roof of the European, Helvetic – Infrapenninic basement to the N and the N-dipping roof of the Adriatic wedge to the S. They constitute an almost rootless body, triangular in cross-section ("Penninic float or lid" of Laubscher, 1994). The internal structure of these nappes is of Late Cretaceous to Eocene age (eo- and meso-Alpine). The penetration of the Adriatic wedge, on the contrary, is a neo-Alpine (Late Oligocene – Miocene) event.

We are thus confronted with one of the greatest enigmas of Alpine geology: where are the lower, proximal parts of the Penninic and Austroalpine nappes? They should contain continental lower crust, part of the upper crust, oceanic crust (ophiolites) and some sediments. Should we look for them below the Adriatic wedge, in front of it or on top of the deep European crust? They may have well been subducted into a depth where eclogite metamorphism renders their seismic distinction from mantle rocks difficult.

The Insubric Line

As already mentioned, the great Insubric fault limits the main body of the Alps against the pre-Permian basement of the Southern Alps. It is subvertical or steeply inclined towards the north. Its young age is exemplified by the juxtaposition of rocks with amphibolite-grade Tertiary metamorphism to the N against pre-Variscan rocks, having suffered only slight Alpine retrograde metamorphism, to the S. Movements along the fault involve a dextral displacement (of about 80 km?) and a strong, top-to-the-S backthrusting, resp. an underthrusting of the Southern Alps.

The fault zone was crossed by two NRP 20 profiles, namely S3 and C2, and two profiles of our international partners, i. e. the CROP-ECORS line across the Western Alps and the Spluga profile of CROP-Italia in the Central Alps. On the sites of the NRP 20 crossings and of the Spluga profile, the fault itself as well as the rock structures on either side are subvertical, so that no relevant reflections could be expected. To our surprise, however, the profile S1 in Val Calanca, some 5 km to the N of the fault outcrop, shows a strong northward dipping reflection which, if properly migrated, would swing towards the outcrop of the Insubric Line. This is a strong indication that the fault, or at least a major component of it, does not remain subvertical at depth but becomes listric and runs northwards underneath the Penninic nappes, as Emile Argand showed already in 1911.

Southern Alps

Only a small portion of the Southern Alps lies in the Swiss canton Ticino. We refer essentially to Chapters 10 and 15 by Schumacher and Schumacher et al. The Southern Alps differ in several respects from the main body of the chain, the most obvious one being that that the thrusts and folds are generally directed toward the S. Their northern part is built up mainly by basement rocks. E of Lake Como, they are affected by thrusts cutting out relatively thin slices (Orobic nappes), whereas further W different steep tectonic planes separate segments with variable basement character. These "lines" are not easy to interpret; some of them may have been rejuvenated. Lower crustal and mantle rocks are exposed in the Ivrea Zone, to the NW of the western segment and not directly within the scope of the NRP 20 profiles; it is often interpreted as the upturned edge of the Adriatic or Apulian plate (Schmid et al., 1989; Zingg et al., 1990; Gebauer et al., 1992).

Mesozoic, particularly latest Triassic and early Jurassic normal faults are conspicuous in this part of the Southern Alps. They generally trend S-N or NNE, downsetting the eastern compartment and presumably flattening at depth. These faults frequently delimit segments with differing Cretaceous and Tertiary tectonic style.

The structures in the Mesozoic sediments are quite characteristic of a marginal thrust-and-fold belt. Ramps are determined by carbonate groups, flats by evaporite or shale levels. Construction of balanced sections, taking into account seismic and borehole information on the Italian side, allows to assess the amount of overall shortening, which is in the order of 100 km (see Schmid et al., Chapter 22). This figure comes close to the shortening in the Helvetic belt. The Helvetic nappes and Subalpine Chains to the N and W, and the Southern Alps to the S and E are late additions to the Alpine edifice.

The age of deformation varies from N to S. In the northern Lombardy Alps, folds and thrusts pre-date the Adamello intrusions, which began at 43 my; circumstantial evidence favours a late Cretaceous rather than an early Tertiary age of these structures. Another climax occurred in Late Oligocene to Early Miocene time. The structures along the exposed front of the Alps are Late Miocene, pre-Messinian. They continue, below the young filling of the Po Valley, into the vicinity of Milano, where they are separated only by a short distance from the northernmost Apenninic, north-verging folds.

1.4 Deep crustal and lithospheric structures

St. Mueller, P. Lehner

NRP 20 was confronted with the general question: what happens to the Earth's crust and lithosphere during continental collision? To study these problems, the Alps, one of the most thoroughly investigated continental col-

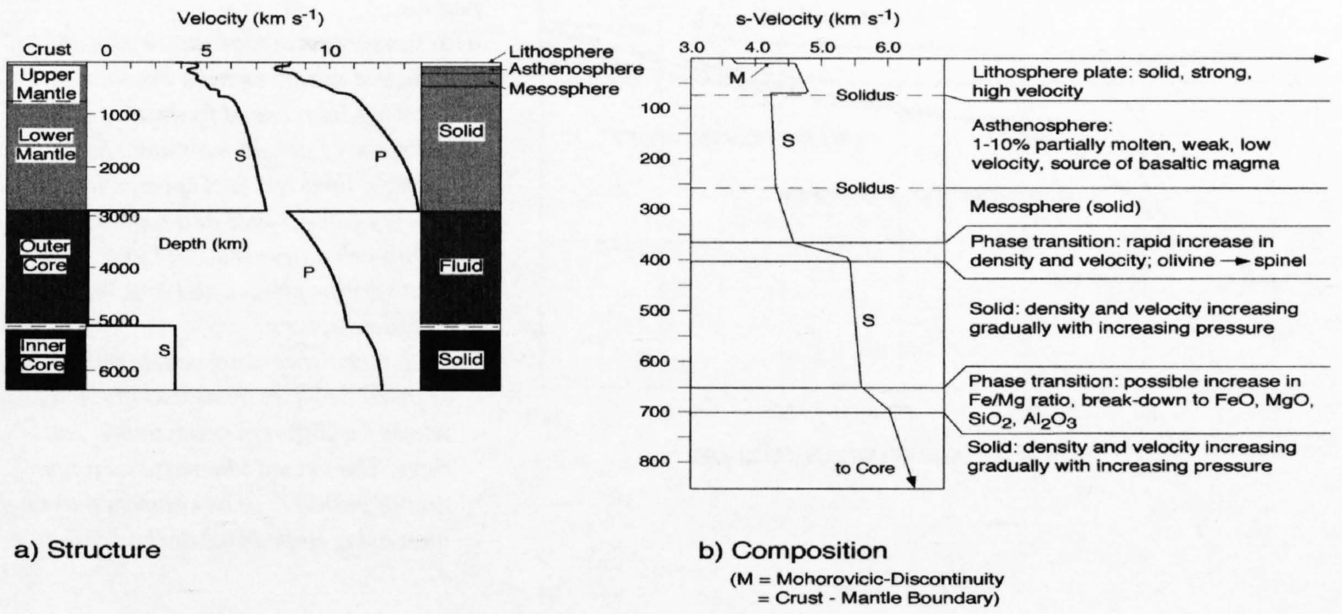

Figure 1-2
A modern view of (a), the structure and (b), the composition of the Earth based on P- and S-wave velocities.

lision zones from the viewpoint of geology as well as geophysics, represent an ideal test case.

The most important event on a global scale during the Alpine collision is unquestionably the formation of thick crustal and lithospheric roots as consequence of lateral compression and crustal shortening. The crust below the Alps has a thickness in excess of 60 km, about twice the thickness of the European crust to the north of the Alps and the Adriatic crust to the south. The corresponding lithospheric root has been traced to a depth of about 200 km.

The systematic mapping of the crustal geometries of the Alps using seismic refraction and wide-angle reflection profiling began in the mid-fifties. These profiles, largely oriented along strike, made it possible to construct a rather accurate map of the base of the crust (the Moho) and to produce a rough picture of its internal structure, specifically its zonation into units of different acoustic velocities. The correlation with surface structures however remained problematic, mainly because of the low resolution of the refraction method.

Of special interest to geologists was the observation, that the Moho undercuts the main axial culmination of the Alpine chain, the Lepontine High, without deviation. To explain the gravity anomaly and uplift of this region, a lower crustal and mantle wedge of higher density had to be introduced. These northward protruding wedges, now confirmed by reflection seismics, constitute the Adriatic wedge.

For the study of the structure of the lithosphere below the Alps to a depth of several hundred kilometers, the depth penetration of signals from man-made explosions is insufficient. Information about those depth ranges is obtained from the regional analysis of seismic surface waves from earthquakes, which illuminate the Alps between the surface and the deeper mantle. They were recorded on an extended network of seismic stations, located around the periphery of the Alps. The obvious advantage of earthquake waves over man-made explosions is their high energy, particularly in the surface wave portion.

At this point it is good to remember that the terms lithosphere and asthenosphere refer to the mechanical behavior of the crust and upper mantle (Figure 1-2). The lithosphere is considered to be solid and brittle at fast strain rates – the asthenosphere soft and partially molten. The Moho discontinuity, which marks the base of the crust is interpreted as a mineralogical discontinuity between the ultramafic peridotites of the upper mantle and the layered sequence of mafic and sialic rocks of the lower crust.

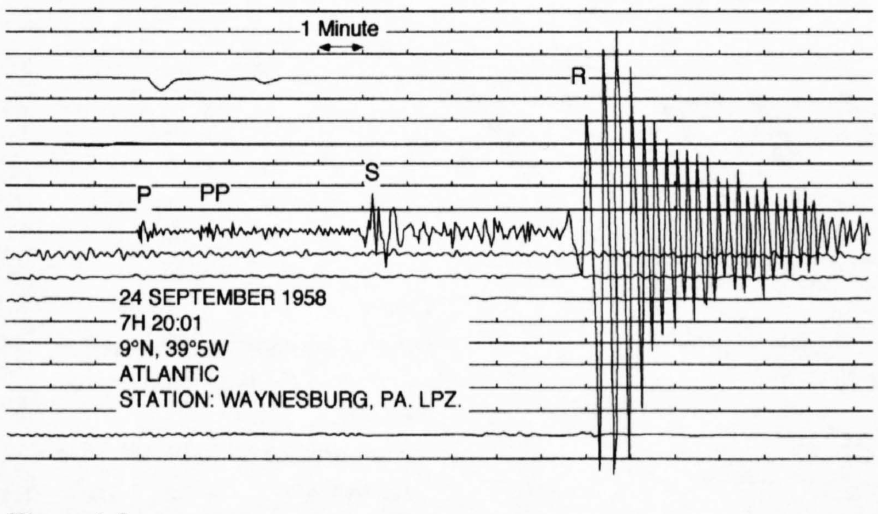

Figure 1-3
Seismogram of an earthquake showing arrivals of various wave types. P: compressional waves, S: shear waves, R: Rayleigh waves.

Most of what is known of the structure within the Earth's interior has been revealed by seismology. Powerful seismic sources, such as earthquakes or large explosions, emit different types of seismic waves: compressional (P-) waves – whose motion is polarized along the wave path –, shear (S-) waves – whose motion is polarized transverse to the wave path – and surface waves – who are guided by the Earth's surface. Each of these wave types represents an elastic response of the medium through which the waves travel. This elastic response is adequately described by the P- and S-wave velocity and the density of the medium. The velocities depend on the elastic parameters of the medium, each of which is a function of pressure, temperature and mineralogical composition. The seismogram in Figure 1-3 shows the long-period (low-frequency) recording of a single earthquake at one locality. The P-waves arrive first, the surface (Rayleigh) waves last.

To investigate the structure of the crust and upper mantle in regions where there are only a few seismic stations located, seismologists generally depend on one type of surface waves, the Rayleigh (R-) waves, whose energy is guided by the Earth's surface and whose travel times depend on the elastic properties and the geometry along the entire path from source to receiver. Seismic surface waves are *dispersive,* i. e. one must distinguish between *phase* and *group velocities*. This means that the low-frequency components of the seismic signal travel faster than the higher frequencies, and from the velocity measurements of the various "instantaneous" frequency components or phases it is thus possible to estimate the structural properties of the propagation medium.

A useful concept in visualizing the mechanism of dispersive wave propagation is to consider an assembly of seismograms that have been obtained at a number of receiving stations at some distance from the source. In Figure 1-4a) the records are all aligned at time t = 0. Each frequency component of the wave train will propagate through the wave train with its appropriate *group velocity* which will be constant for a given frequency component and different for different frequencies. The location of a given frequency component in the wave trains from successive receiving stations will thus plot on a straight line (cf. solid lines in Figure 1-4a) through the origin. The slope of these lines will be the group velocity. Such lines have been drawn for three different frequency components in Figure 1-4a).

If one traces a particular phase in each wave train from record to record – such as the first four troughs shown as dashed curves in Figure 1-4a) – they plot on curves all passing through the origin. It is obvious that each phase (or "trough") is associated with a different ("instantaneous") frequency from one record to the next. In Figure 1-4a) the frequency is seen to decrease with distance for a particular phase of the wave train. The slope of the dashed curves at any chosen point in the distance-time plane will be the *phase velocity* for the particular frequency component associated with that point.

A systematic study of large-scale heterogeneous features in the lithosphere-asthenosphere system did not begin until the late 1950's, when the first networks of standardized wide-band seismometers were installed. Surface-wave data from these networks quickly convinced seismologists that there are regional differences in structure, in particular between oceans and continents (shields, cratons and orogenic zones; see Figure 1-4b). Throughout most of the crust and upper mantle the elastic parameters (wave speeds and density) increase with depth because the pressure squeezes the rock into tighter, more rigid structures. Under ocean basins and active orogenic zones, however, the shear (S-) wave velocity was found to decrease sharply with depth in a transition zone that begins about 50 to 100 kilometers below the surface and forms a "low-velocity zone" (or "channel") approximately 100 kilometers

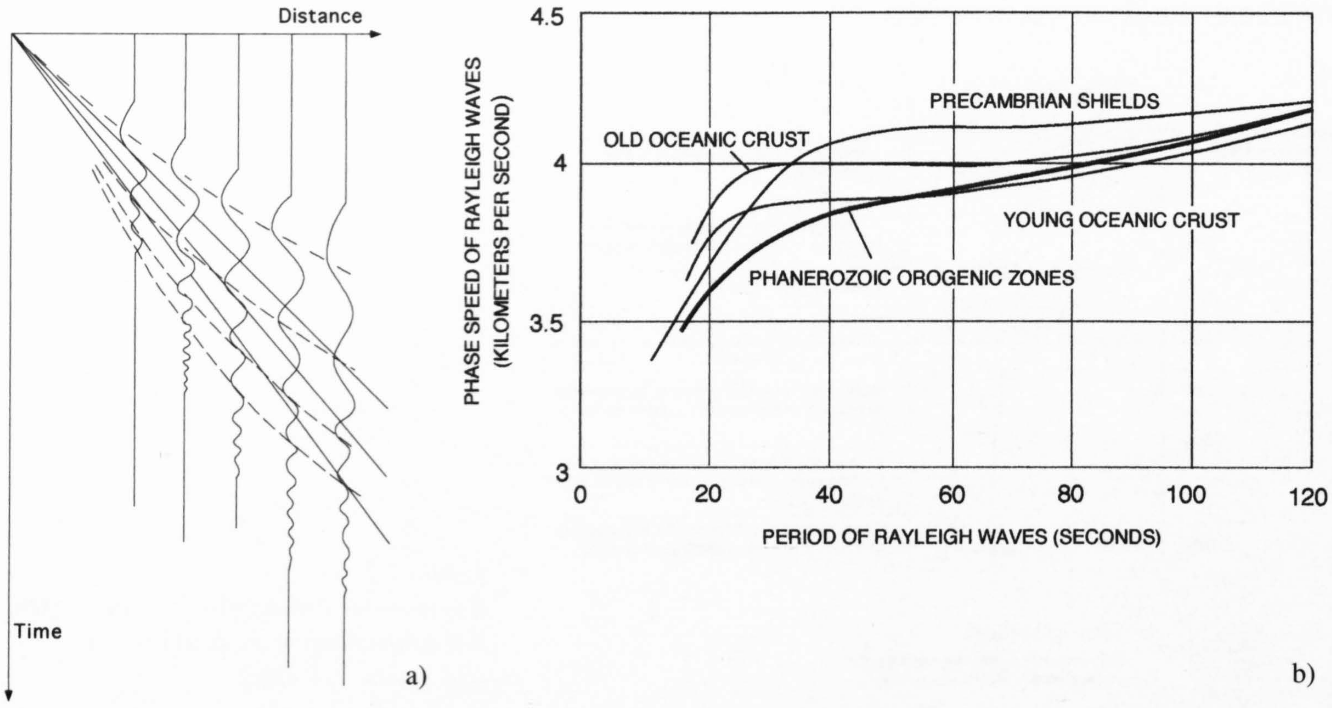

Figure 1-4
Schematic display of Rayleigh-wave dispersion.
- *a) Seismograms of four stations located at different distances from the source, showing increase of frequency, resp. decrease of period with time. Solid straight lines connect specific frequency components and represent group velocities. Dashed curves connect specific phases and thus represent phase velocities.*
- *b) Graph showing observed dependency of phase velocity on period of Rayleigh waves for different geodynamic settings. The velocity increase as a function of period is to be compared to the increasing slope of the dashed curves in a).*

thick. These seismological findings agreed quite well with the accepted models of the thermal state and electrical conductivity of the upper mantle. Wave speeds generally vary with temperature, i. e. a small amount of melting results in a dramatic decrease in the shear modulus, and thus in the S-wave velocity.

This structural picture of the upper mantle, which emerged in the early 1960's fitted very well into the developing concepts of sea-floor spreading and plate tectonics. Seismologists identified the easily deformable asthenosphere ("channel") with the partially molten material in the "low-velocity zone" and associated the rigid lower lithosphere ("lid") with the cooler material above the "low-velocity zone". It became clear that by mapping the depth to the "low-velocity zone" seismologists were actually mapping the geographical variations in lithospheric plate thickness. This model does, of course, imply that plate motions should continually be rearranging the tectonic configuration by moving the lithospheric material with respect to the asthenosphere, thereby introducing regional variations in the structure of the lithosphere-asthenosphere system.

On true scale cross-sections the Alpine morphology, as impressive as it may be, by human standards, appears almost negligible compared to the enormous size of a so-called lithospheric root, which like a heavy and cold anchor plunges way down into the asthenosphere. There can be no doubt about its important role in Alpine convergence and collision tectonics.

A new phase of crustal investigations began in 1986 with the NRP 20 seismic reflection program and the EGT long-range refraction line, which on Swiss territory runs parallel to the eastern traverse of NRP 20 (E1)and was recorded simultaneously.

The combination and cross-correlation of three sets of geophysical data (Figure 1-5) namely:

- stacked and migrated near-vertical reflections
- migrated wide-angle reflections
- migrated refractions

made it possible to obtain a coherent and more accurate picture of the internal structure of the Alps and correlate the results with the near-surface geology. The correlation of the deep crustal structures with the surface geology represented a crucial and long awaited-for step in the study of Alpine tectonics. Theories based on surface data could now be compared and tested against models derived from geophysical measurements and vice versa.

The new profiles indicate that the continental crust under lateral compression has a tendency to split up and delaminate along more or less distinct detachment zones at mid-crustal level. Under lateral compression this may lead to large-scale imbrications of crustal slabs or to wedging.

Potential detachment zones commonly show up as significant, abrupt changes of seismic velocities or even velocity reversals. The related impedance contrast across such boundaries may also enhance their reflectivity.

Detachment tectonics is well known from the folded and overthrusted sedimentary section in the external zones of the Alps and the adjacent sedimentary basins. Typical detachment zones are the Triassic evaporites, near the base of the Alpine sedimentary section or thick shale layers within the Mesozoic and Tertiary sequence. With respect to the deeper structure of the Alps the question must be asked: is the Earth's crust also mechanically layered and, if yes, how does it react as it enters into the Alpine collision zone?

The intact continental crust below the Swiss Molasse Basin, in the foreland of the Alps, is about 30 km thick. It can be subdivided into two distinct zones of nearly equal thickness, namely – a laminated lower crust, with a band of strong reflections near its base and – a more or less transparent upper crust (Figure 1-6).

The external massifs, which frame the arc of the Western Alps to the north and west represent detached and upthrusted slabs of upper crust, stripped off the subducting lower crust. A similar phenomenon is observed along the southern rim of the Alps, where slabs of Adriatic upper crust, peeled off from the steeply northward plunging lower crust are thrusted upward and southward towards the Po Basin. The Adriatic lower crust is intensely deformed as it plows into the subducted European crust.

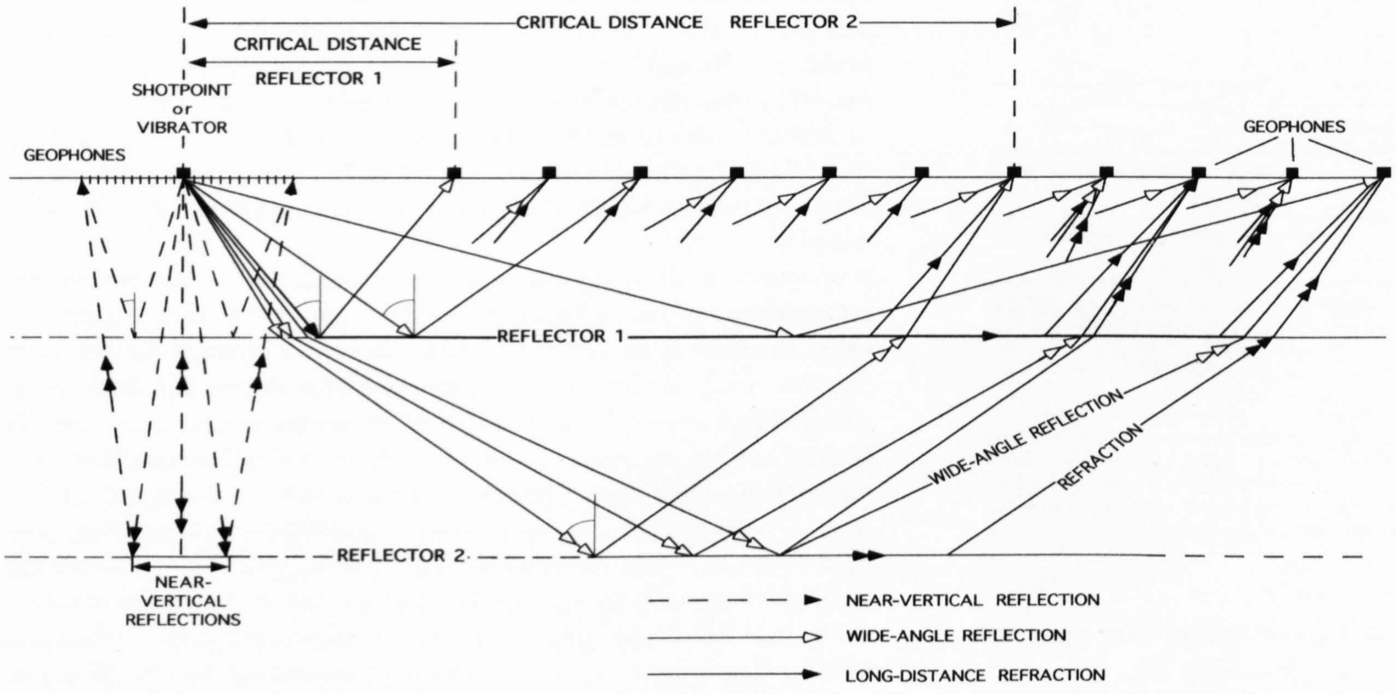

Figure 1-5
Diagram explaining the layout geometries of the three main seismic methods:
- *High-angle, near-vertical reflection seismology*
- *Wide-angle reflection seismology (beyond the critical distance)*
- *Refraction seismology*

1.5 Bedrock topography and clastic fill of Alpine valleys

P. Lehner

As a contribution to the study of Alpine morphology and morphogenesis a number of experimental, high-frequency, low-energy profiles, with a very dense station spacing were recorded across the generally flat and level valley floors of three main Alpine streams, namly the Rhine, the Rhone and the Ticino. The aim was to obtain information about the depth and morphology of the bedrock surface and the nature of the clastic valley fill. This valley fill is of importance for questions concerning groundwater flow, water resources and pollution. From a morphological point of view the so-called overdeepening of the Alpine valleys, both within and in the immediate periphery of the Alps, in the course of the Pleistocene glaciations is of particular interest. The depth of the bedrock below the clastic valley fill of the overdeepend portions of the Rhone, Aare, Rhine and Ticino rivers reaches locally several hundred meters below present sea level, with clastic valley fills up to 1 km thickness. NRP 20 tried to explore the finer structure of these valley fills to get insight into the origin and evolution of these valleys.
An additional set of high frequency profiles were recorded in the southern Ticino near the Italian border across the sites of suspected Pliocene or possibly Miocene buried valleys.

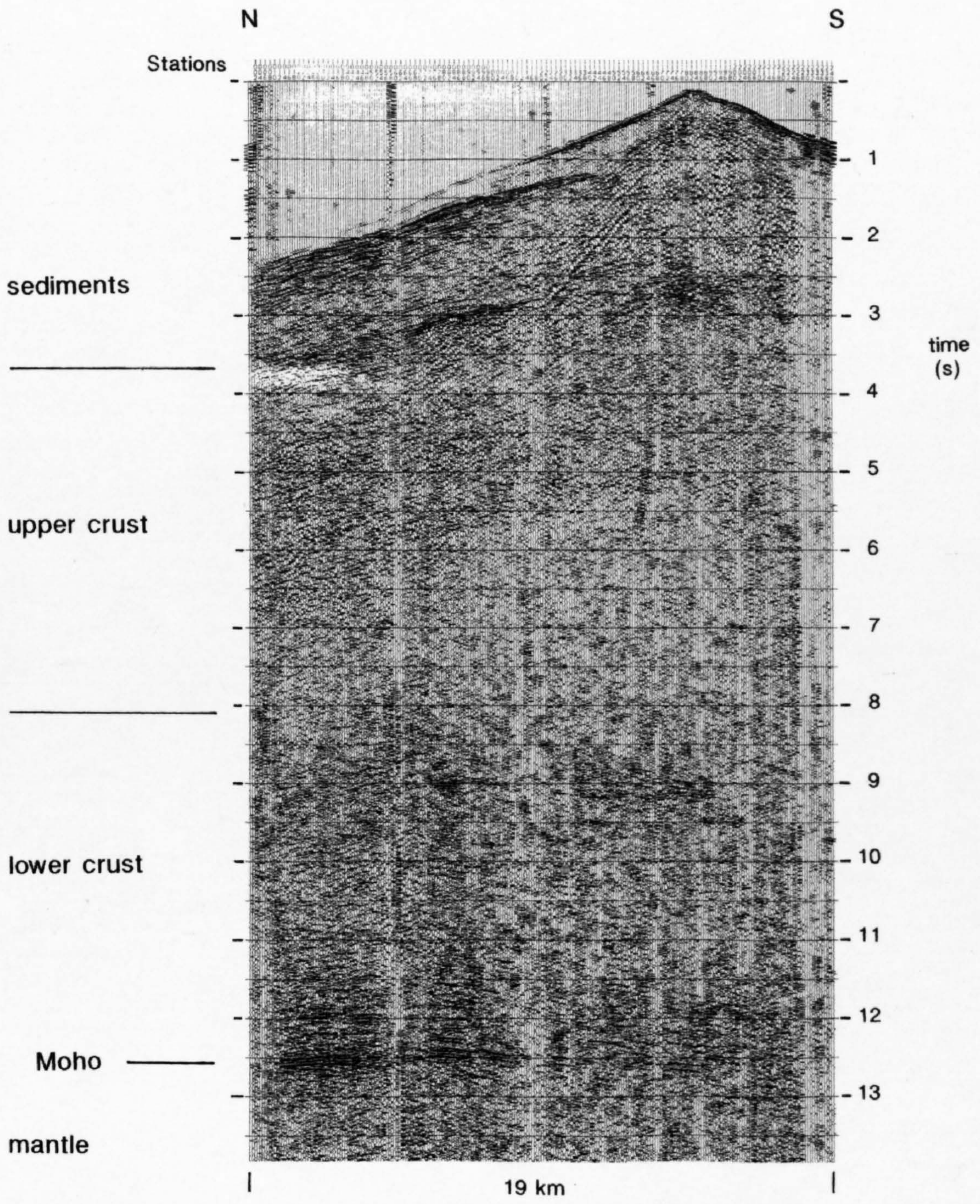

Figure 1-6
Seismic reflection profile of a single dynamite shot near Sevelen in the northern part of the eastern traverse (compare Fig.12-2, 13.1-4 and 13.1-5). Note the so-called transparent upper crust below the "top basement" reflection at around 3 sec TWT, down to the acoustically layered lower crust from approx. 6 sec TWT to the top of the mantle (Moho) at 13 sec TWT. The base of the lower crust is commonly marked by a zone of strong reflections.