The Swiss geotraverse Basel-Chiasso : a review

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Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **73 (1980)**

Heft 2: **Symposium alpine geotraverses with special emphasis on the Basel-Chiasso profile : Lausanne, 4-5 October 1979**

PDF erstellt am: **08.05.2024**

Persistenter Link: https://doi.org/10.5169/seals-164965

Eclogae geol. Helv.	Vol. 73/2	Pages 437-462	6 figures in the text	Basle, July 1980

The Swiss Geotraverse Basel-Chiasso - a review[1])

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ABSTRACT

The Swiss Geotraverse Basel-Chiasso represents a multidisciplinary approach, within the framework of the International Geodynamics Project (IGP), to unravel the present and past geodynamic development of the Central Alps and of its foreland. Methods involved include geology, geophysics, mineralogy/petrology, geodesy and geochronology. The line Basel-Chiasso indicates the general axis of the traverse (total length: 220 km) which cross-sects the main geologic units of Switzerland: the Rhinegraben, the Tabular and Folded Jura mountains, the Molasse basin, the Helvetic nappes, the Central crystalline massifs with their autochthonous cover, the Penninic units (= the deepest exposed units) and, south of the Insubric Line (a major geotectonic lineament), the crystalline and sedimentary units of the Southern Alps. A synoptic compilation and comparison of the results, including structural geology, recent vertical crustal movements, seismicity and stress field, seismic sections, gravity data and temperature profiles, is presented.

ZUSAMMENFASSUNG

Die Schweizer Geotraverse Basel-Chiasso stellt einen breitgefächerten Beitrag zum International Geodynamics Project (IGP) dar, mit dem Ziel, die geodynamische Entwicklung der Alpen und des Vorlandes anhand eines ausgewählten Profils zu erfassen. Die Untersuchungen einer besonderen Arbeitsgruppe in den Jahren 1974-1979 erstreckten sich über die Fachgebiete Geologie, Geophysik, Mineralogie/Petrologie, Geodäsie und Geochronologie. Die Linie Basel-Chiasso repräsentiert die generelle Achse der Traverse (Totallänge: 220 km), welche die tektonischen Hauptelemente der Schweiz durchquert: Rheingraben, Tafel- und Faltenjura, Molassebecken, Helvetische Decken, Zentralmassive mit Autochthon, Penninische Einheiten (= tiefste aufgeschlossene Einheiten) und - südlich der Insubrischen Linie - die kristallinen und sedimentären Einheiten der Südalpen. Es wird eine synoptische Darstellung der Resultate, einschliesslich Strukturgeologie, rezente Erdkrustenbewegungen, Seismizität, tektonisches Spannungsfeld, seismische Profile, gravimetrische Daten und Temperaturprofile, präsentiert.

TABLE OF CONTENTS

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1. Introduction

The investigations along the Swiss Geotraverse Basel-Chiasso reported in this volume have been performed within the general framework of the *International Geodynamics Project* (IGP). It has been one of the specific aims of the IGP to focus attention on selected traverses: "*Geotraverses.* Major effort should be devoted to systematic surveys in selected areas, using geophysical, geochemical and geological techniques. They should be oriented towards those areas where specific problems need to be solved; and it may often be desirable not to restrict these surveys to uniform linear bands." (Comments of the International Geodynamics Commission, IGP Report No. 3, 1972.)

In 1974 the Swiss National Committee for the IGP established, on the proposal of Prof. E. Niggli (Bern) a Working Group "Geotraverse Basel-Chiasso". The primary aim of this Working Group was to initiate, coordinate and concentrate multidisciplinary research on this Geotraverse through Switzerland with a view to a synoptic compilation and representation of the structure, deformation, metamorphism and geodynamic evolution of the Alps and its foreland. The composition of the Working Group, comprising structural geologists and geophysicists, mineralogists and geochemists, geodesists and geochronologists, as well as the interaction of its members warranted a broad-based approach to the manifold problems.

The initiation of the Swiss Working Group took place at a time which has seen several concentrated efforts on different traverses in many parts of the world. The nearest - and especially successful - example was the Geotraverse IA (Chiemsee-Vicenza, see also ANGENHEISTER, this volume) through the Eastern Alps. The accomplishments of the Working Group "Geotraverse Basel-Chiasso" were only possible due to a decisive coordination and to the close cooperation of the actively contributing members.

The profile trace between Basel and Chiasso was selected on the basis of several criteria, of which the most important one was the aim to transect, entirely on Swiss territory, as great a number of contrasting geologic/tectonic units as possible. The profile so selected has, of course, advantages as well as disadvantages. The Geotraverse Basel-Chiasso crosses, more or less perpendicularly to the main tectonic units (Jura mountains, Molasse basin, Alps) the deepest exposed parts of the Central Alps: the crystalline massifs and the Penninic units in greenschist/amphibolite metamorphic grade. On the other hand, higher tectonic units like the Austroalpine nappes cannot be investigated and represented along the Geotraverse. Even within the units traversed there are complications: e.g. the steeply dipping structures of the Maggia nappe are cut by the traverse at low angle. However, there is hardly a single straight profile trace which would account for all the aspects of the complex region in question.

The first presentation of research activities and results from the Geotraverse area was given at a special Symposium which was jointly organized by the Swiss Geological Society and by the Swiss Mineralogical and Petrographical Society. The "Symposium Geotraverse Basel-Chiasso" took place in Geneva on 9 October 1976. 22 papers were given; most of them are published in Schweiz. mineral. petrogr. Mitt. *56*, 555-707: OBERHOLZER, W., & RYBACH, L. (Ed.): Symposium "Geotraverse Basel-Chiasso". *Inter-Union Commission on Geodynamics Scientific Report No. 37.* The final results of the Working Group have been presented at the Symposium "Alpine Geotraversen - mit besonderer Berücksichtigung des Basel-Chiasso-Profils" in Lausanne, 4-5 October 1979; most of the contributions are assembled in this volume.

New, complementary traverses have been initiated recently, one on each side of the Geotraverse Basel-Chiasso: the traverses Brig-Sesto Calende (Italy) and Besançon (France)-Biella (Italy) in the west and the traverse Konstanz (Federal Republic of Germany)-Clusone (Italy) in the east. The results of the investigations along these traverses will certainly shed light on the central Geotraverse as well.

Since the Geotraverse Basel-Chiasso passes through the numerous complex geologic units of the Central Alps, it represented a unique opportunity to contribute fundamentally to the understanding of the geodynamics of prominent geotectonic features and thus to the International Geodynamics Project in general. The results will form a substantial starting base for the international cooperative program to follow the IGP in the 1980's.

2. Geologic-tectonic units

Along its length of 220 km, the Swiss Geotraverse Basel-Chiasso transects a series of well-defined geologic-tectonic units approximately perpendicular to their strikes (Fig. 1). It encompasses a complete section through the Alpine chains, including parts of the northern foreland and the hinterland to the south. Here we summarize the general structural features of these units in succession from north to south (numbering as in Fig. 1).

1. The *Rhinegraben* is a continental rift structure filled by up to 2 km of Tertiary and Quaternary sediments at its southernmost end, where it reaches into Switzerland in the Basel area. The initiation of graben formation dates back to the late Eocene; substantial parts of the Rhinegraben system (especially its northern section) has been reactivated in a new stress field in Miocene times. The southern section of the Rhinegraben (south of Freiburg) was inactive since the lower Miocene (Burdigalian), although even today the graben zone exhibits increased seismicity and high terrestrial heat flow.
2. The *Jura mountains* south of Basel can be subdivided into two main structural units, the "Tabular" Jura to the north and the Folded Jura to the south. The "Tabular" Jura consists of an autochthonous Mesozoic cover lying unconformably on the buried southern extension of the Black Forest pre-Mesozoic basement. South of a major thrust zone lies the Folded Jura, consisting of the same

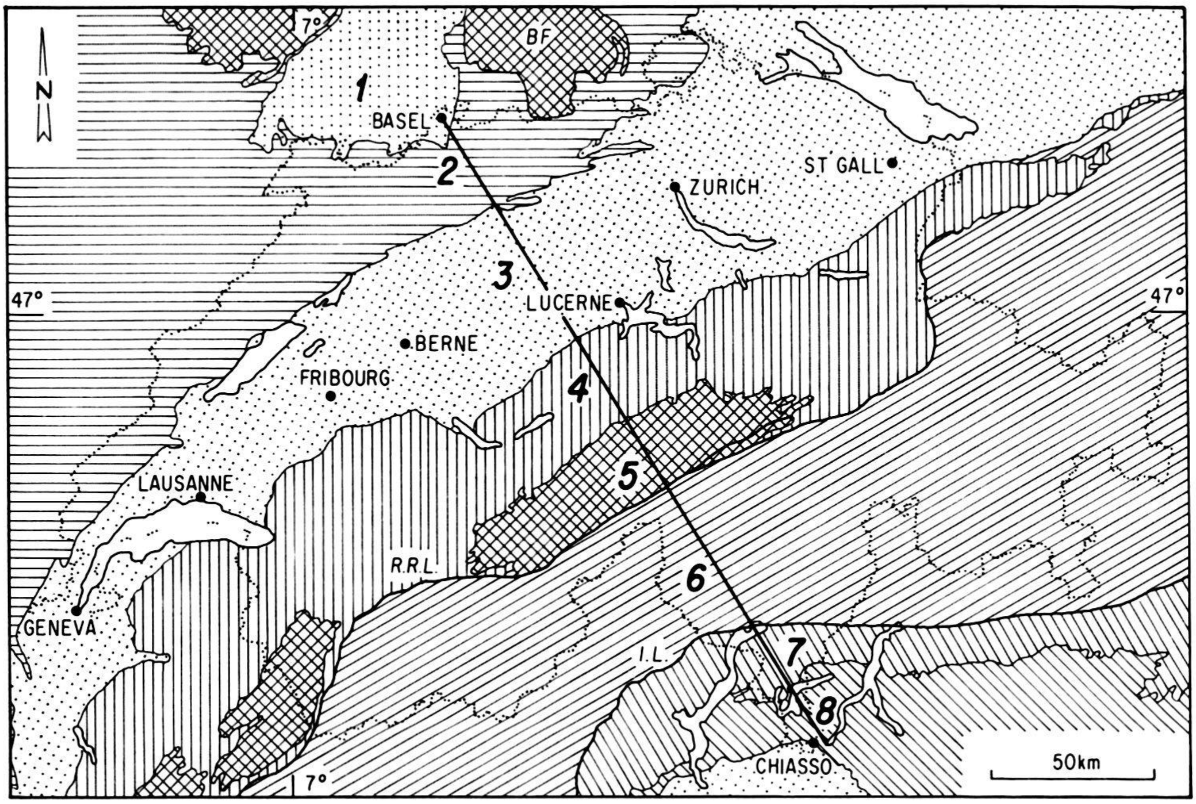


Fig. 1. The profile trace of the Swiss Geotraverse Basel–Chiasso crosses the main geologic units (1 = Rhinegraben, 2 = Jura mountains and undeformed foreland cover, 3 = Molasse basin and Subalpine Molasse, 4 = Helvetic nappes and remnants of Penninic cover rocks, including the autochthonous to parauthochthonous cover of the external massifs, 5 = external massifs, 6 = Subpenninic, Penninic and Austroalpine units, 7 = south-Alpine basement, including the Ivrea zone, 8 = south-Alpine cover) more or less perpendicularly to the general strike direction. *BF* = Black Forest Massif, *R.R.L.* = Rhine–Rhone Line, *I.L.* = Insubric Line (after RYBACH 1976).

cover rocks, now uncoupled from the basement and transported northwards with the formation of relatively simple thrust-and-fold structures. The movement took place in late Miocene to Pliocene times and is superimposed on earlier faults related to the formation of the Rhinegraben. The basement below the Jura mountains is nowhere exposed, and there is no information from drill holes, but it is assumed to consist of Hercynian granites, gneisses and migmatites, similar to those of the Black Forest. The basement surface dips gently in a SSE direction under the Molasse basin (Fig. 2, 3), where it and its detached, Jura-type Mesozoic cover form the fundament of that unit.

3. The *Molasse basin* is the Tertiary fill of the large depression between the Black Forest basement high and the main Alpine chains. The oldest Molasse (Lower Marine Molasse) is of mid-Oligocene age. This is overlain by three other lithostratigraphic units: Lower Freshwater Molasse (upper Oligocene to lower Miocene), Upper Marine Molasse (late lower Miocene) and Upper Freshwater Molasse (middle to early upper Miocene). Lithologies vary from calcareous shales and sandstones to coarse conglomerates, with marked coarsening and thickening from north to south. The south side of the basin shows complex

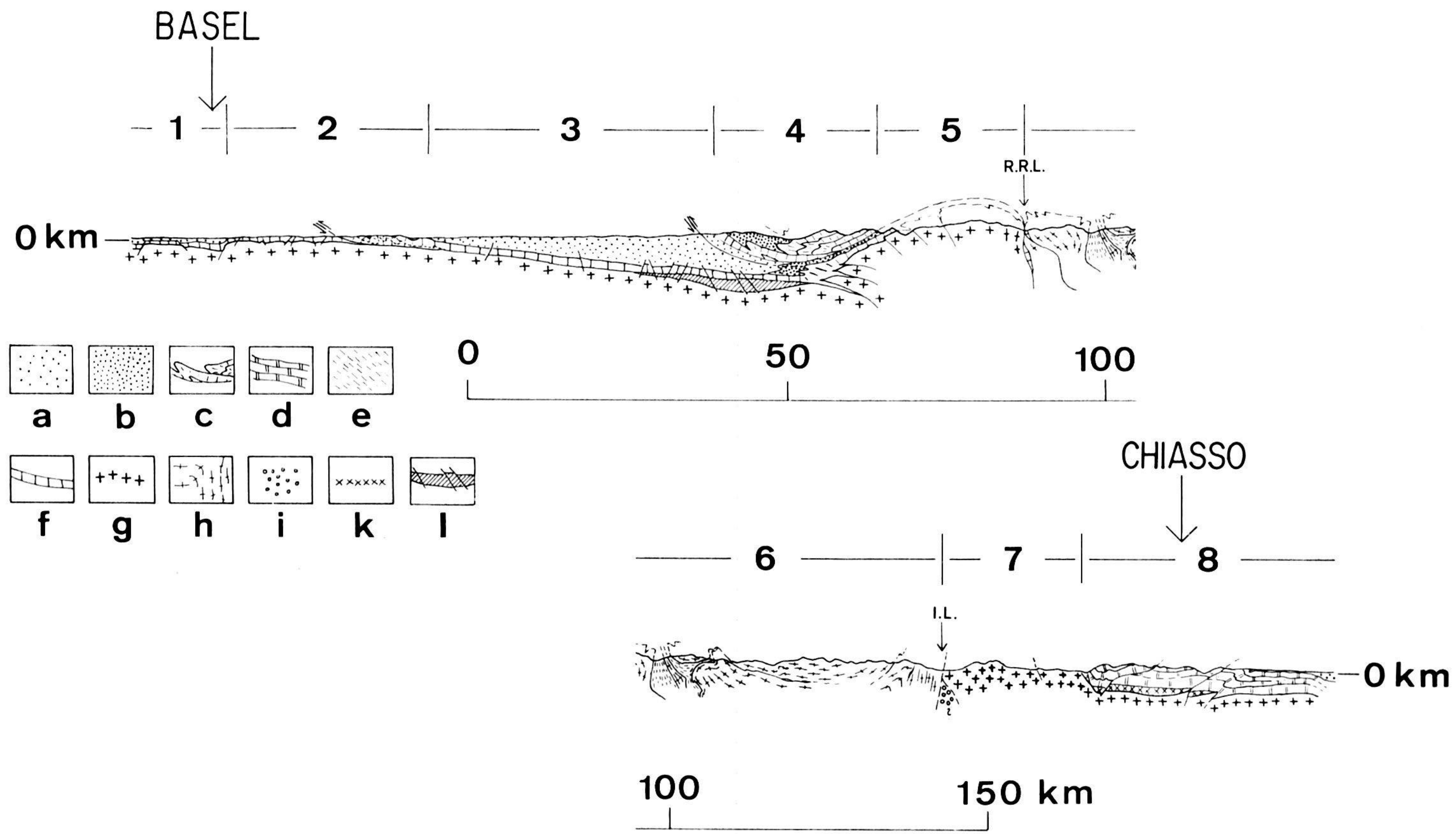


Fig. 2. Geologic profile along the Geotraverse Basel-Chiasso (from BÜCHI & TRÜMPY 1976; modified after BEB 1979). No vertical exaggeration. The units 1-8 correspond to those in Figure 1. *a* = Molasse sediments, *b* = flysch sediments, *c* = Mesozoic sediments of the Helvetic nappes, *d* = Mesozoic sediments of the Southern Alps, *e* = Mesozoic sediments of the Penninic units, *f* = Mesozoic sediments of the Jura mountains and of the autochthonous cover of the Aar Massif, *g* = crystalline basement including external massifs, *h* = intensely deformed basement of the Penninic zone, *i* = ultrabasic rocks of the Ivrea zone, *k* = Upper Paleozoic volcanites, *l* = Permocarboniferous sediments.

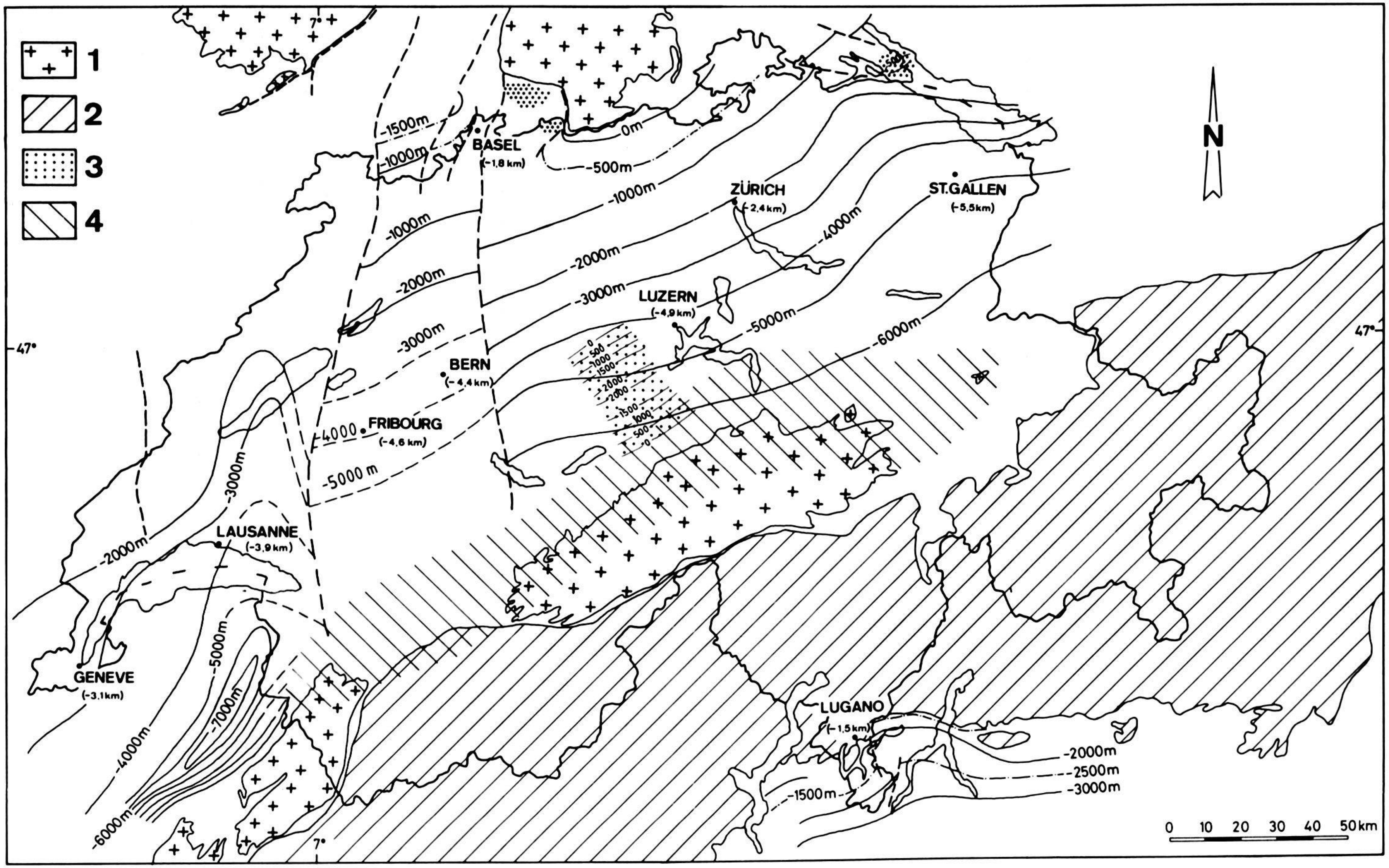


Fig. 3. Contour lines of the crystalline basement below the Jura mountains and the Molasse basin. Figures in brackets: depth, contour lines refer to sea level. 1 = crystalline massifs, 2 = rocks with low primary permeability, 3 = Permocarboniferous troughs (partly schematic; with isopachs), 4 = zone of superposition (external massifs partly thrusted over the foreland basement). From Rybach et al. (1980).

relations between sedimentation and tectonics (Fig. 2). There, the coarse clastics are syn-orogenic with respect to the Neo-Alpine orogeny (mid-Oligocene to Pliocene) and were subsequently overridden by nappes from the south and transformed into a deformed wedge (Subalpine Molasse).

4. The *Helvetic nappes* along the Geotraverse line lie in a structural depression between the Molasse (unit 3) and the Aar Massif (unit 5). They are made up of Mesozoic limestones and Tertiary flysch derived, except for a thin, autochthonous cover, from a region south of the massif (including some Penninic elements from much further south, corresponding to unit 6), giving a northward overthrust displacement of 40 km or more. These movements resulted in complex thrusting and internal folding of the various nappes and probably took place during the Miocene (see MILNES & PFIFFNER, this volume). Some units show a very low-grade metamorphism whose isograds are cut and displaced by the main thrusts.
5. The *external massif* crossed by the Geotraverse is the Aar Massif, an old (Caledonian) metamorphic basement complex containing infolded Permo-Carboniferous sediments and intruded by two generations of Hercynian acid plutons. This basement is unconformably overlain by a thin autochthonous to parautochthonous Mesozoic cover and thick Tertiary flysch (included in unit 4). Surface outcrops show the effects of heterogeneous Alpine deformation and low-grade metamorphism, both increasing from north to south. In the eastern Aar Massif this is dated as late Oligocene, i.e. predating the deformation and overthrusting of the Helvetic nappes. The external massifs seem to be detached from the foreland basement and are apparently upthrusted (BEB 1979, MENARD 1979; see also ROEDER, and AYRTON, both in this volume). Subsurface information indicates a ductile flow zone at depth, probably related to the Jura decollement (late Miocene to Pliocene; see Fig. 2). The southern margin of the Aar Massif is a prominent suture, the Rhine-Rhone Line, representing the very attenuated connection between the Helvetic cover nappes (part of unit 4) and their subducted continental basement (the tip of which preserved to the east as the Tavetsch "Massif"). This suture is also the site of minor faulting (Quaternary). The complicated Alpine structural and metamorphic history of units 4 and 5 is summarized in chapter 7 of this review.
6. *The Subpenninic, Penninic and Austroalpine nappe complex* is mainly represented by pre-Mesozoic continental basement rock of the Pennine zone in the region of the Geotraverse (the Lepontine area), completely overprinted by Alpine polyphase deformation and metamorphism. Some Mesozoic rocks are involved, however, and indicate intense shredding or ductile interleaving of basement and cover at an early stage in the orogenic history (see also HOMEWOOD et al., this volume). The Geotraverse line (Fig. 1) does not allow a clear representation of the large-scale structural complexities of this zone - some aspects of these are treated in more detail below (chapter 7 of review). Evidence from both sides of the traverse suggests a long evolution starting in the mid-Cretaceous and ending in the early Oligocene, associated with the closing of a small ocean and the subsequent collision of the continental margins. Post-Oligocene movements are

concentrated along its northern and southern boundaries - "backfolding" adjacent to the Rhine-Rhone Line (during the Neo-Alpine orogeny, see units 4 and 5 above), and the development of the steep zone ("root zone") and the Insubric Line in the south. This latter is a now inactive fault zone, with associated mylonites and cataclasites, with a downthrow to the south of 15-20 km since the Oligocene and possibly with some strike-slip displacement.

7. The *South Alpine basement* consists of three well-defined zones separated by Hercynian (possibly Alpine-rejuvenated) faults. To the north lies the Ivrea zone - mainly mafic rocks and granulite facies metamorphics thought to represent a slab of Hercynian lower crust/upper mantle. Only a very thin slice of this zone is exposed along the Geotraverse section. To the south of the Ivrea zone lies the Strona-Ceneri zone, mainly gneisses in amphibolite facies, and to the south of this a zone of low-grade schists and phyllites. Some Carboniferous sediments lie unconformably on this old basement, overlain by thick Permian volcanics and clastic sediments. Alpine effects within this whole complex are confined to diaphtoresis near the Insubric Line and faulting and thrusting associated with the cover deformation (unit 8). There is some evidence that the Ivrea body already lay at an unusually high level in the crust before the start of Mesozoic sedimentation.
8. The *South Alpine cover* comprises the pile of marine sediments overlying (unit 7), with the 1500 m thick Middle Triassic at its base. Synsedimentary block faulting and shallow water sediments are typical of the older formations (up to upper Triassic). These are followed by pelagic sediments (lower Jurassic to lower Cretaceous) and later by deep-water clastics (upper Cretaceous to Eocene). Alpine deformation took place by decollement along the Triassic evaporite horizons during the late Miocene. The Pliocene-Quaternary sediments of the Po plain are undisturbed.

3. Crustal movements, gravity

Ongoing tectonic activity in the Alpine area manifests itself, among other phenomena, by recent crustal movements. Although there is little information on the horizontal component of these movements the *vertical* component can be evaluated by repeated geodetic levelling. First-order levelling data, determined by the Swiss Federal Topographic Survey, are available since 1903 (JEANRICHARD 1972). The changes in height (relative to a specific reference station in the Molasse basin near Aarburg) have been converted to vertical uplift/subsidence rate in millimeters per year (GUBLER 1976). The calculation of the uplift/subsidence rate is based on the assumption of constant rate over the time periods in question.

The profile of the Geotraverse Basel-Chiasso is dominated by *uplift* in the area south of Luzern (see Fig. 6, second diagram from top) whereas no uplift/subsidence can be determined (within measurement accuracy) in the northern foreland. From Luzern at the northern border of the Alps the uplift rates increase towards the Lepontine area, reach there a maximum of 1.5 mm/y and decrease again towards the south. No significant change in the uplift pattern can be seen in crossing the Insubric Line (*I.L.* in Fig. 6). The offset which appears near the Rhine-Rhone Line

(*R.R.L.*) might well result from the fact that the uplift data have been projected onto the section of the Geotraverse from considerable distances. The wavelength of the uplift curve is substantial; it calls for a relatively deep-seated cause of the crustal movements.

Modern *gravity* data are available from the area crossed by the Geotraverse Basel-Chiasso since the completion of the new gravimetric survey of Switzerland (KLINGELÉ & OLIVIER 1980). The *Bouguer anomaly* profile between Basel and Chiasso is given in Figure 6. The pronounced minimum (– 150 mgal) is located near the Rhine-Rhone Line; the maximum north of the Insubric Line is due to the contribution of the Ivrea body (with an anomalously high density) west of the traverse. The edge effect of the Ivrea body in the profile of the Geotraverse Basel-Chiasso amounts to about +40 mgal; a further effect (approx. –30 mgal) can be attributed to the (low-density) Molasse sediments in the northern part of the Geotraverse (see KAHLE et al., this volume).

Regional *isostatic anomalies* have been described by KAHLE et al. (1980). In the section of the Geotraverse Basel-Chiasso negative isostatic anomalies prevail south of Luzern (KAHLE et al. 1976*b*) and they reach –20 mgal. In general there is a close correlation between uplift rates and (negative) isostatic anomalies, although edge effects of the Ivrea body complicate a straightforward relationship.

The uplift of the Central Alps can either be caused by a) vertically acting isostatic rebound or b) more horizontally acting tectonic forces (e.g. the push of the African plate from the south, causing compression and in turn upbulging) or by a combination of both factors. Two-dimensional plain strain model calculations (NEUGEBAUER et al., this volume) revealed that the uplift pattern as observed along the Geotraverse Basel-Chiasso can mainly be attributed to the first factor; the model applied leads to an uplift pattern along the Geotraverse which closely fits the observations.

Besides spatial changes in the uplift pattern, *variations in time* are of particular interest. Metamorphic mineral reactions, radiometric age determinations and the distribution of heat producing radioelements represent the necessary data base to investigate the uplift/cooling history of a given area. Distinct regions of the Central Alps like the Monte Rosa, Simplon, Leventina and Bergell areas show a nonuniform uplift history (WAGNER et al. 1977) with different timing in the onset of individual uplift phases. Model calculations, assuming erosion rates to be equal to uplift rates (WERNER, this volume), revealed that, besides the differences in timing, there are three main phases in uplift/erosion history: a) an initial period with high uplift/erosion rates (up to 2 mm/y), b) a relatively quiescent period and c) a final phase with moderate uplift/erosion, in accordance with today's geodetic observations of the ongoing uplift. For the Lepontine area (which is cross-sected by the Geotraverse Basel-Chiasso) the timing of the initial period of high uplift rates was from 22 to 18 million years ago, with a quiescent period from 8 to 2 million years ago (WERNER 1979).

4. Stress field, seismicity

The present-day *stress field* of the Swiss Alps as well as of the northern foreland is governed by compression with nearly horizontal *P*- and *T*-axes (PAVONI 1976).

The direction of the Geotraverse Basel-Chiasso corresponds to the direction of maximum horizontal compression of the regional stress field in the upper crust (N 160° E), as revealed by earthquake fault-plane solutions and in-situ stress determinations (PAVONI 1979). The fault-plane solutions indicate that within and outside the Alps strike-slip motions predominate. The NNW-SSE orientation of maximum horizontal compression is a general feature in Central and Western Europe and has been essentially constant during the last 5-10 million years. In the region of the Geotraverse Basel-Chiasso the isolines of crustal uplift rates as well as the gravity isolines (Bouguer and isostatic anomalies) are more or less perpendicular to the stress field trajectories (PAVONI 1979).

Composite fault-plane solutions of microearthquakes in the Central Valais area (western part of the Rhine-Rhone Line) correspond closely to the compression/extension pattern which can be deduced from displacements on neotectonic faults cutting through the Helvetic nappes (PAVONI, this volume).

In-situ stress determinations (strain release measurements, see ILLIES & GREINER 1978) have also revealed that considerable excess horizontal compressive stress is present in the upper crust of the Swiss Alps (see also Fig. 6, second diagram from top): whereas low values (< 5 MPa) prevail in the northern foreland, the excess horizontal stress increases from the border of the Alps (near Luzern) to about 25 MPa in the Lepontine area to decrease again towards the south. The shape of the stress pattern corresponds well with the uplift pattern (MUELLER et al. 1976).

If *seismicity* is considered as a manifestation of the present stress field in the frame of the acting tectonic systems, the distribution of earthquakes along the Geotraverse Basel-Chiasso shows some peculiarities. In the north some earthquake activity is present in the region of Basel and in the Jura, probably related to the Rhinegraben system. The Molasse basin further to the south is characterized by low seismic activity. A prominent zone of seismicity is present at the northern limit of the Central Alps, especially north of the Aar Massif, and has been interpreted by PAVONI (1977) as a Cenozoic hinge zone between the uplifting Alps and the (relatively) stable foreland. South of the Aar Massif seismic activity is low to normal; in the section of the Geotraverse Basel-Chiasso neither the Rhine-Rhone Line nor the Insubric Line shows any distinct seismicity. Focal depths along the Geotraverse are in general shallow: the earthquakes cluster in the depth range of 5-15 km.

The same two-dimensional plain strain model which has been applied to constrain the vertical uplift observed along the Geotraverse Basel-Chiasso to topographic loads and isostatic rebound (NEUGEBAUER et al., this volume) leads to a shear stress distribution with a maximum in the Gotthard area. In the same region the maximum principal stress shows a steeply dipping orientation and corresponds to the "hinge zone" of PAVONI (1977) south of Luzern; to the north and to the south the maximum principal stress is oriented at low angles to the horizontal.

5. Structure of crust and upper mantle

The current efforts to determine the structure of the crust and upper mantle under the Alps in a European cooperative program date back to the first detailed refraction seismic measurements in the Western Alps in 1956. The data accumulated since – a considerable amount of it obtained with modern recording techniques and by digital data processing – allowed to construct a detailed crustal cross section of the *P* wave-velocity distribution down to a depth of 60 km between the Rhinegraben and the Po Plain along the Swiss Geotraverse as described in this volume by MUELLER et al. The crustal information could be extended recently by additional data from long-range seismic refraction measurements, from the dispersion analysis of seismic surface waves and the interpretation of *P*-delay observations down to a depth of more than 200 km, i.e. the base of the asthenosphere.

By far the most abundant crustal information comes from a large number of seismic refraction profiles most of which run more or less parallel to the strike of the main geologic and tectonic units, i.e. perpendicular to the Geotraverse. A few cross-strike profiles connect the structure under the southern Rhinegraben and the Folded Jura mountains with the Central Alps and the Po Plain. Supplementary information comes from a few areas with near-vertical deep reflection observations.

Figure 6 shows the lithospheric cross section along the Geotraverse as it was derived from seismic data. The crust/mantle boundary dips down towards the southeast from a shallow mantle upwarp with a depth of 25 km under the southern Rhinegraben to about 40 km depth under the northern margin of the Alps and about 50 km under the Central Alps. The area between Basel and Luzern is characterized by a "normal" continental crust as found in tectonically active areas (MUELLER 1977) with an upper crustal low-velocity layer and a second zone of reduced velocity in the transitional depth range above the Moho.

Under the Aar Massif this type of crust seems to have been strongly affected by the Alpine orogeny. An upper crustal flake has apparently been bent upwards which nowadays is visible in the central granitic core of the Aar Massif with higher metamorphosed material in its southern envelope. The lower crust extends probably from the north down under the Pennine block of the Central Alps between the Rhine–Rhone Line and the Insubric Line. Whether two separate crustal slabs are superimposed on each other or a stack of several crustal slices is pushed into each other like a deck of cards cannot be decided from the presently available data. This complicated crustal structure characterized by a low average velocity under the Central Alps is supported by the highly metamorphosed units found at the surface which must have been uplifted by 20–25 km. Only detailed near-vertical seismic reflection measurements will provide the clue for a better understanding of the structure in this area.

The asymmetric relief of the crust/mantle boundary along the Geotraverse with its deepest part under the Pennine block is in good agreement with the observed gravity anomalies (KAHLE et al. 1976*a*, *b*).

South of the Insubric Line the crust/mantle boundary is found at a depth of about 35 km under the Southern Alps. The higher average crustal velocity strongly indicates that this area has preserved its characteristic feature as a "rift flank"-type structure which must have resulted from extensive rifting in lower Jurassic time, followed by spreading from middle Jurassic to the early Cretaceous (BÜCHI & TRÜMPY 1976).

The deformation of the crust/mantle boundary is the acute symptom of a much deeper reaching velocity anomaly. Long-range seismic refraction observations in the northern Alpine foreland and along the main strike of the Alps in addition to the detailed analysis of the dispersion of surface waves and further evidence from the observation of *P*-wave travel time residuals reveals a deep-reaching anomalous distribution of *P*- and *S*-wave velocities.

North of the Alps a layer with a high *P*-wave velocity of up to 8.5 km/s and a thickness of the order of 10 to 15 km lies on top of a relatively shallow upper boundary of the asthenosphere located at depths between 50 and 60 km (Ansorge et al. 1979; Sprecher 1976). Under the Alps this depth range of high velocity seems to increase in thickness and to become more differentiated by the appearance of at least two layers of high *P*-wave velocity within the depth range of at least 100 km of the upper mantle (Miller et al. 1979).

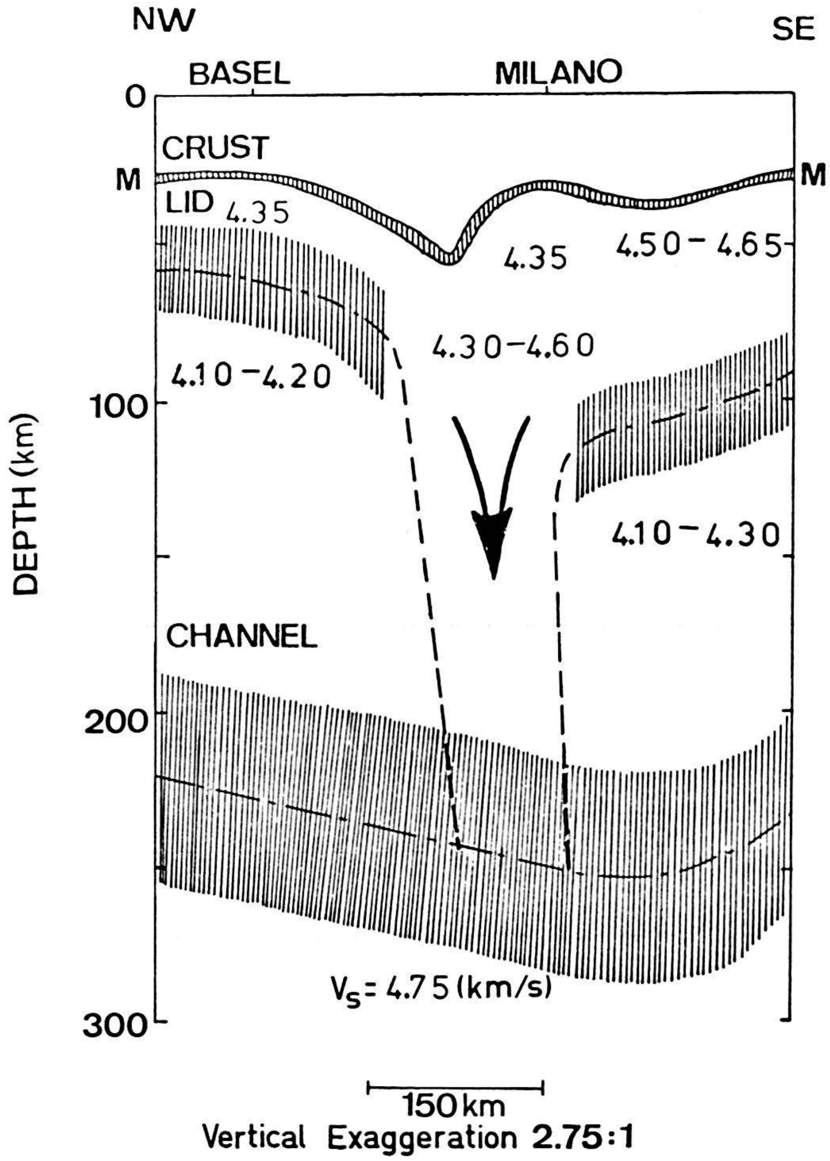


Fig. 4. *S* wave-velocity cross section from Basel to Milano as derived from the simultaneous inversion of all available dispersion data of seismic surface waves. Hatched area indicates the range of uncertainty of crustal, lithospheric and asthenospheric boundaries, after Panza & Mueller (1979).

On a much larger scale the observation of a high-velocity block within the upper mantle under the Alps could be deduced from the dispersion of seismic surface waves by PANZA & MUELLER (1979). Figure 4 shows a schematic cross section of the lithosphere and asthenosphere system along a profile from Basel to Milano which coincides roughly with the Swiss Geotraverse with the hatched areas marking the range of uncertainty for the bottom of the crust, the lithosphere and asthenosphere. The center is characterized by a high-velocity subducted lower lithosphere reaching down to the bottom of the asthenosphere at a depth of about 250 km. This lithospheric block of higher velocity most likely corresponds to the two slabs of lower lithosphere subducted during the plate collision process ("Verschluckung") forming the Alps (PANZA & MUELLER 1979).

A crust/mantle model of this type not only provides a reasonable solution for the deposition of the excess lithospheric material which must have been displaced during the shortening of the Alpine crust/mantle system, but it also gives an explanation for the apparently nonexisting difference in the P-wave travel time residuals of teleseismic events observed at stations in the Alpine foreland and in the Alps (BAER 1979). Figure 5 demonstrates that the proposed model with a high-velocity block in the uppermost mantle will provide the required compensation for the extra delay caused by the much thicker crust under the central portion of the Alps. It should be noted that the zone of near-vertical subduction or subfluence

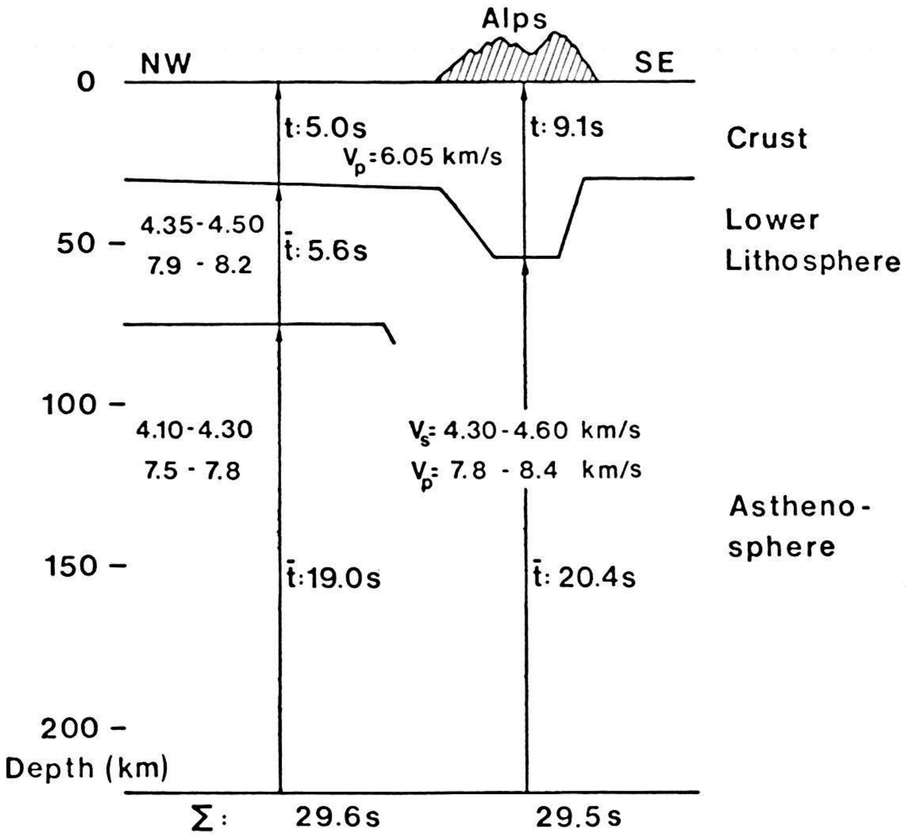


Fig. 5. Schematic NW-SE cross section through the Central Alps after PANZA & MUELLER (1979) and one-way travel times between the surface and lower boundary of the asthenosphere after BAER (1979). ($V_p/V_s = 1.82$ after SPRECHER 1976.)

(Verschluckungszone after AMPFERER 1906) is not symmetrical with respect to the central zone of the Alps, but appears to be somewhat displaced towards the south-east, i.e. the inner side of the Alpine arc.

6. Heat flow, geothermal field

Heat flow determinations near the Geotraverse Basel-Chiasso have been compiled in RYBACH & FINCKH (1979) and are plotted in Figure 6 (bottom diagram): triangles indicate heat flow determinations in lake bottom sediments and those performed in drillholes, shafts, and tunnels are represented by dots. The heat flow trend along the Geotraverse is characterized by lower values in the central part of the section. Roughly the same heat flow prevailed apparently at the times of peak metamorphism (Neo-alpine event): from the "geothermal gradients" as deduced from p/T data from metamorphic mineral reactions along the Geotraverse (FREY et al. 1976) and by assuming an average crustal thermal conductivity of 2.5 W/m, K one obtains heat flow values in the range of 63–112 mW/m^2 which plot surprisingly close (open circles in Fig. 6, bottom diagram) to today's heat flow trend.

The heat flow values reported for the Molasse basin seem unusually high (Lake of Zürich: 125 mW/m^2; Lake of Zug: 123 mW/m^2). Until very recently there were no further heat flow determinations available from the Molasse basin (using e.g. drillhole information) and data were also lacking from the Jura mountains. Very recently, a number of thermal conductivity determinations have been performed (SCHAERLI 1980) which allows heat flow estimates to be made on the basis of geothermal gradient data. For the Jura region near Basel a heat flow value of about 100 mW/m^2 results (based on a geothermal gradient of ~35 °C/km; see RYBACH & BODMER, this volume) whereas for the Molasse basin the average is about 90 mW/m^2 (based on a gradient of 30 °C/km as measured in a 730 m deep drillhole in Zürich).

A characteristic feature of the *geothermal field* in the section of the Geotraverse Basel-Chiasso is the decreasing geothermal gradient/heat flow from the foreland towards the Alps. (It is worth noting here that a similar trend has been reported for the Pyrenees and the Guyenne-Gascogne area north of it; GABLE 1979.) Model calculations of the temperature field at greater depth, based on deduced or assumed thermal parameters of the lithosphere (RYBACH et al. 1977), have revealed that below the Central Alps there is possibly a remaining thermal disturbance due to subduction tectonics ("Verschluckung"); the downwarped 1000 °C-isotherm in Figure 6 (bottom diagram) illustrates this. It is most likely that heat flow into the Alpine crust from deeper levels in the upper mantle will be lower in the section with the thickest crust than at the northern and southern flanks with more normal crustal thickness.

Numerous new heat flow determinations are still needed to draw a realistic picture of the geothermal conditions in an area which encompasses such complex geologic/tectonic features as the Alps, especially in view of the thermal effects of uplift/erosion (see WERNER, this volume). Also the heat transfer by convection must be carefully considered. Convective effects can be expected not only in regions with thermal springs but also in areas where orographically controlled water circulation might occur over a considerable depth range (see OXBURGH & ENGLAND, this volume).

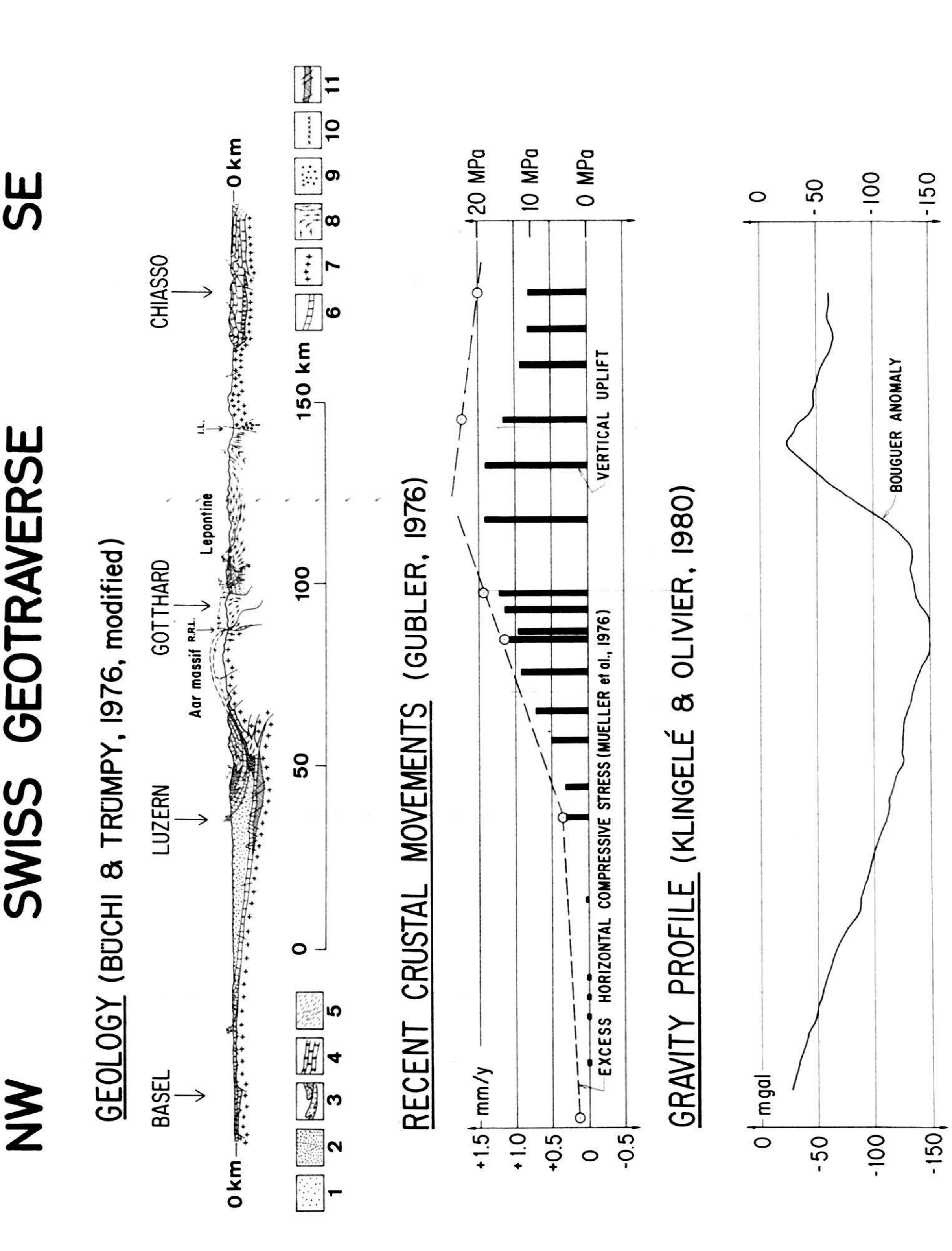
7. Deformation phases

Numerous papers both in the earlier Geotraverse Symposium (OBERHOLZER & RYBACH 1976) and in this volume have shown that the complex structure produced by the Alpine orogeny can only be understood in terms of a succession of "phases". The word "phase" is used here in a purely structural sense, indicating geometrically recognizable stages in a sequence of deformational events, without any implication of the relation between one stage and the next. The relation between such phases, i.e. whether overlapping, continuous or temporally separated movements, can sometimes be deduced using additional microstructural, stratigraphic and/or geochronologic data (e.g. AYRTON & RAMSAY 1974; HUNZIKER 1970; MILNES & SCHMUTZ 1978), but the available information along the Geotraverse is scanty in this respect. For the purposes of describing the Geotraverse relations, two segments will be discussed in which the sequence is now well established and for which there are indications on general grounds that the timing was different. These are a) the Infrahelvetic/Helvetic complex (Fig. 1, units 4 and 5), deformed mainly during Oligocene-Miocene times (Neo-Alpine orogeny), and b) the Subpennine/Pennine/Austroalpine nappe complex (Fig. 1, unit 6), deformed during late Cretaceous and early Tertiary times (Eo- and Meso-Alpine orogenies) and only marginally affected by movements younger than mid-Oligocene.

a) Infrahelvetic/Helvetic complex

The main ductile phase of Alpine deformation in the Aar Massif and its autochthonous/parautochthonous cover (which together with some small but significant allochthonous units forms the *Infrahelvetic* complex, i.e. the complex lying below the *Helvetic* nappes) resulted in a pervasive cleavage and associated structures which can be followed continuously from eastern to western Switzerland, across the Geotraverse transect. In the east it is known as the Calanda phase (MILNES & PFIFFNER, this volume), whereas in the west the resultant schistosity is designated S_1^A (STECK et al. 1979). The deformation produced a series of deep infolds of cover rocks into the Aar Massif basement (e.g. Fernigen, Innertkirchen, Jungfrau) and major fold and thrust structures in the cover at higher levels (absent along the Geotraverse). A pronounced stretching lineation developed at the same time, roughly parallel to the dip of the cleavage (steep southeast in the basement and to the south, more gently southeast in the cover to the north) and at a high angle to the fold axes. This main phase of ductile deformation events - it postdates the deposition of the Engi slates in Glarus (lower Oligocene) and predates the growth of chloritoid porphyroblasts on the south side of the Aar Massif (and Oligocene/Miocene boundary). Other events in the structural history of the whole complex can be conveniently subdivided into two groups, older and younger respectively than this main deformation.

Structures *predating* the main phase have not been recognized along the Geotraverse. Two earlier events can be distinguished in eastern Switzerland - both also



NW SWISS GEOTRAVERSE SE
GEOLOGY (BÜCHI & TRÜMPY, 1976, modified)
BASEL
LUZERN
GOTTHARD
CHIASSO
Aar massif
R.R.L.
Lepontine
I.L.
0 km
0
50
100
150 km
1 2 3 4 5 6 7 8 9 10 11
RECENT CRUSTAL MOVEMENTS (GUBLER, 1976)
mm/y
+1.5
+1.0
+0.5
0
-0.5
20 MPa
10 MPa
0 MPa
VERTICAL UPLIFT
EXCESS HORIZONTAL COMPRESSIVE STRESS (MUELLER et al., 1976)
GRAVITY PROFILE (KLINGELÉ & OLIVIER, 1980)
mgal
0
-50
-100
-150
BOUGUER ANOMALY

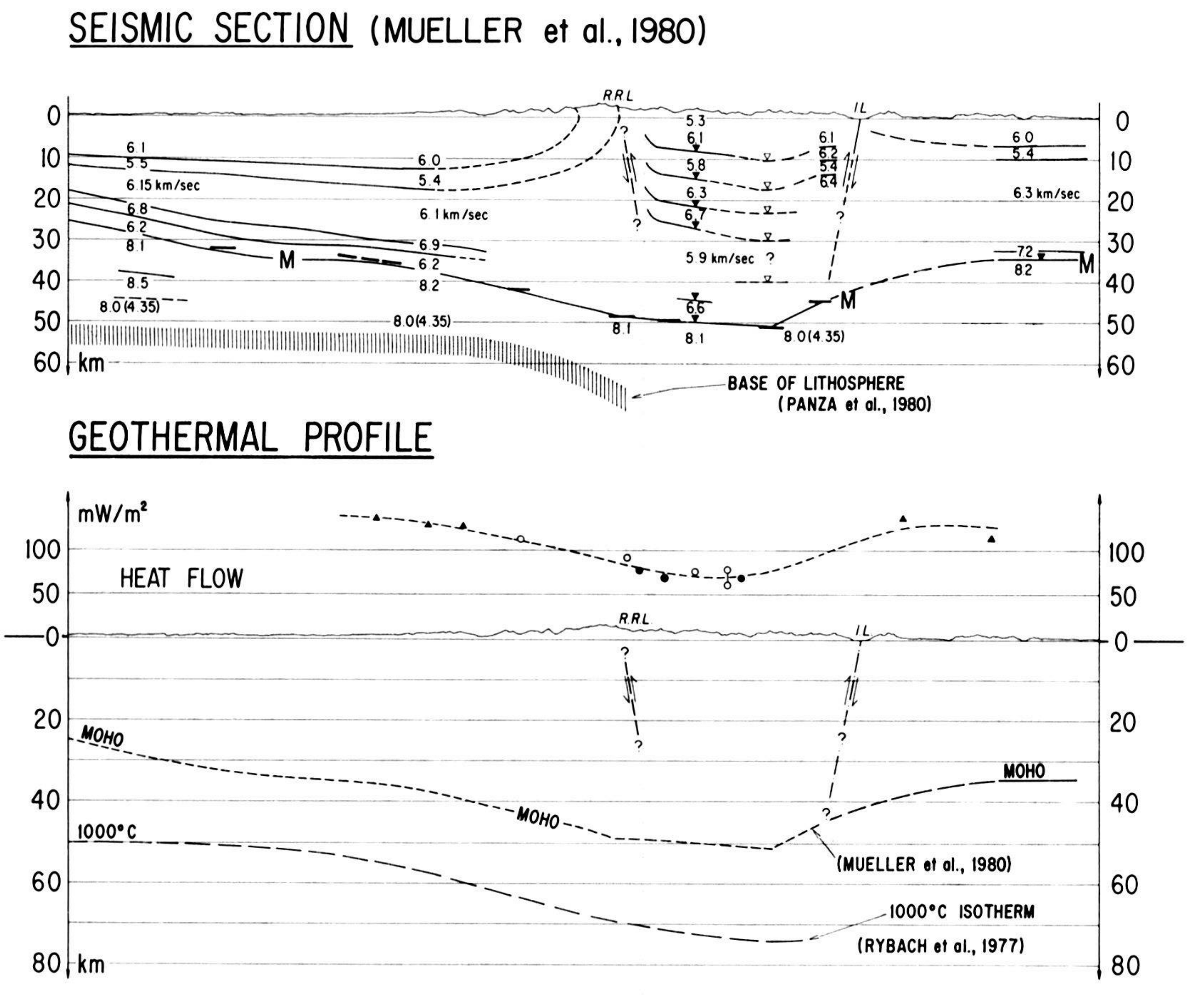


Fig. 6. Synoptic representation of the Swiss Geotraverse Basel-Chiasso. The units 1-11 (top diagram) are the same as units a-l in Fig. 2. For detailed discussion see text.

younger than the deposition of the Engi slates - the emplacement of far-travelled nappes (Ultrahelvetic) and the formation of more locally derived recumbent folds, both with basal thrusts or inverted sequences deformed by main phase structures (MILNES & PFIFFNER, this volume). In contrast, a whole plethora of minor and major structures *postdating* the main phase have been reported, both along the Geotraverse line (e.g. STECK 1968) and to both sides. The emplacement of the Helvetic nappes on top of the Infrahelvetic complex, and the corresponding subduction of the Helvetic basement, is the main result of these later phases. The relations are best seen in Glarus and in the Reuss valley where the basal Helvetic thrust sharply truncates the main phase cleavage. This cleavage is also affected by later deformation to form crenulation cleavages which can sometimes be related to major structures (e.g. the Glarus thrust in the Ruchi-Hausstock group, major refolding of the Windgällen syncline below the Hüfi glacier), but which are often sporadically and unsystematically distributed. In the Aar Massif basement, whole sequences of later structures can be distinguished (crenulation cleavages, kinks, shear planes) but they are difficult to relate to major movements (STECK 1968). All these effects are probably Miocene or younger, some of the later ones possibly Pliocene, related to major underthrusting at depth (Fig. 2).

b) Subpennine/Pennine/Austroalpine nappe complex

South of the Aar Massif, the Geotraverse crosses a deeply eroded complex of gneisses and high-grade metamorphic rocks (Fig. 1, unit 6) which to the east and west can be differentiated into three main zones: *Subpennine* (including the Gotthard and Lucomagno "Massifs"), *Pennine* and *Austroalpine* (in the west consisting of the Dent Blanche nappe and the Sesia zone). Both east and west of the Geotraverse, the structural history of these zones can be unravelled much more easily (see HOMEWOOD et al., and MILNES & PFIFFNER, this volume). Difficulties arise along the Geotraverse itself because the Mesozoic cover rocks are poorly differentiated and make up only a minor part of the whole complex, and because the metamorphism was so intense (FREY et al., this volume). Mainly high-grade gneisses are intersected, representing more or less strongly alpinized basement. These are also poorly differentiated, so that much of the zone was earlier referred to as the Lepontine gneiss complex. Polyphase folding on both minor and major scales is a characteristic feature of the zone and leads to a complicated three-dimensional geometry which cannot be satisfactorily represented on a single section. For instance, the apparently flat-lying gneisses in the central part of the section (Fig. 2) are in fact dipping at high angles *towards* the observer (the line of section is here subparallel to the strike). This in turn warns against direct correlations between this apparent structure and seismically determined subhorizontal layering in this area (cf. Fig. 6). Unfortunately, a complete study of the structural relations across the whole complex has not yet been carried out. The following scheme is at the best a possible framework for future studies, at the worst, a misleading oversimplification.

Studies in the northern part of the complex (HUBER et al., this volume) have revealed a regional structural history which can be described in terms of three phases, each having produced large scale flow structures:

Phase 1 ("nappe formation"): interleaving of basement and cover by intense slicing and/or isoclinal folding, and superposition of cover units from different facies belts (Subpennine/Pennine), widespread small scale isoclinal folding and transposition foliations.

Phase 2 ("post-nappe folding"): strong folding of phase 1 structures on all scales, particularly well seen where cover intercalations act as marker horizons, widespread small scale similar-type folds, axial-plane schistosities and coaxial mineral lineations.

Phase 3 ("backfolding"): large scale open folding which produced a regional asymmetrical synform with a steep northern limb and a more gentle southern limb, widespread chevron-type minor folding with sporadic development of crenulation cleavage.

The complicated overall geometry in three dimensions results from the fact that the folds developed in these phases are not generally coaxial. A similar sequence of structural events with similar geometrical results can be distinguished in the south, although this section has not been studied in detail. The structural (but not necessarily temporal) equivalent of phase 3 resulted in an asymmetrical antiform, its steep southern limb being the so-called "root zone". At least two phases of earlier folding can be distinguished here as well, although again these may or may not be temporal equivalents of the phase 1 and 2 structures further north. In the south, there is also evidence of major post-phase 3 movements in the form of strong mylonitization adjacent to the Insubric Line.

The high temperature conditions indicated by the mineral parageneses throughout the complex (FREY et al., this volume) are though to have prevailed from about 38–23 my ago (i.e. from beginning to end of the Oligocene). Microstructural evidence indicates that the phase 2 structures above were formed shortly before or at the beginning of this time (HUBER et al., this volume). This implies that phase 2 is a Meso-Alpine event, associated with the main Alpine continent/continent collision, and is clearly earlier than the post-lower Oligocene deformation of the Infrahelvetic/Helvetic complex to the north. Otherwise, the timing of the remaining phases along this part of the Geotraverse is a matter of conjecture.

8. Tectonic evolution

The post-Hercynian tectonic and metamorphic evolution of the Central Alps is determined, by and large, by the relative motions of the African and Eurasian plates and the smaller plates (Iberia, Apulia) occurring along their boundary zone. The kinematics of these plate movements are closely linked to the creation and destruction of oceanic crust and lithosphere in the Atlantic–Tethyan system (e.g. BIJU-DUVAL et al. 1977; LAUBSCHER & BERNOULLI 1977).

In early Triassic times (220 my), the Alpine–Mediterranean area probably existed as a unified landmass with a continental crust of normal thickness. From the central Atlantic area to the western Mediterranean area and central Europe, Permo-Triassic deposits are predominantly continental with episodic shallow-marine incursions. To the southeast thick marine sediments, deposited on continental crust, are transitional to a large marine, probably oceanic area between Eurasia and Gondwana (Paleotethys). Middle to late Triassic extensional tectonics and volcanic activity in the Southern and Eastern Alps are generally interpreted as early phases of abortive rifting (BECHSTÄDT et al. 1978).

Tethyan events

The early evolution of the Mesozoic Tethys is closely related to the opening history of the central Atlantic that was initiated about 180 my ago. Opening in the Atlantic was connected with an essentially sinistral motion of Africa with respect to Eurasia and with the contemporary evolution of a small N-S-trending ocean basin in the realm of the later Apennines and Alps (Liguria-Piemont ocean). The paleotectonic evolution of the continental margins of this ocean was characterized by listric and normal faulting during an early, Liassic, phase of rifting, followed by long-lived subsidence as a consequence of crustal thinning and cooling. The Jurassic-early Cretaceous sedimentary evolution of the margins closely parallels that of passive Atlantic-type undeformed margins and was mainly determined by ongoing synsedimentary faulting and increasing water depth (BERNOULLI et al. 1979; GRACIANSKY et al., in press). Local uplifted blocks and long-lived active fault-scarps associated with marine breccia formations (Falknis nappe, Breccia nappe) point to the interference of transverse movements, particularly along the northern (transform) margin of the Liguria-Piemont ocean. By the late early Cretaceous (110 my) the extension of the *oceanic* area of the Tethys in the transsect of the Central Alps must have reached several hundred kilometers and the points corresponding to today's Basel and Chiasso on the Geotraverse were probably more than 1000 km apart (LAUBSCHER & BERNOULLI 1977).

Eo-Alpine events

The turn from passive Atlantic-type continental margins to active margins governed by compression and/or large-scale lateral movements occurred during the "middle" Cretaceous (110 my). This change is obviously connected with the initiation of spreading in the south Atlantic and the associated counterclockwise rotation of Africa, and with the opening of parts of the north Atlantic (Iberian margin, Bay of Biscay) in the wake of the rotation of Iberia. The Cretaceous orogenic movements, however, are only poorly known and are mainly inferred from indirect evidence, such as radiometrically dated metamorphic events and from allochthonous flysch sediments and their clastic content.

Abundant chromite mineral grains in Cretaceous flysch sequences (FLÜCK 1973) and ophiolite olistoliths in sedimentary melanges (CARON et al., in preparation) suggest the obduction of ophiolites during the middle/late Cretaceous orogeny, and the restriction of this ophiolite detritus to Austroalpine (Gosau; OBERHAUSER 1968) and south-Pennine clastic sequences indicates that the orogenic movements occurred along the southern margin of the Tethyan ocean (LAUBSCHER 1970). The general contemporaneity of radiometric dates of high-pressure, low-temperature metamorphism in the south-Pennine-Austroalpine (Sesia) units of the Western Alps

(HUNZIKER 1974) suggests lithospheric subduction at that time and a general arc-trench environment for at least some of the flysch deposits. Basel and Chiasso are now still some 600 km apart.

Indications for such an Eoalpine tectonic and metamorphic event along the Geotraverse are scarce because the much higher Pennine and Austroalpine nappes in which these events are recorded are eroded or cut-out by the Insubric fault zone in our transsect. However, eclogites and garnet peridotites are fairly widespread in the Adula-Cima Lunga zone and record *P/T*-conditions of the upper mantle (EVANS & TROMMSDORFF 1978). These rocks could be remnants of Hercynian or pre-Hercynian events, but in view of their low alteration it is more probable that they record an early Alpine event. Considering the complex deformation in the adjacent areas to the west and the east (Schams) with its complicated involution of higher nappes, a south-Pennine provenance of these rocks is a plausible hypothesis.

Whole rock Rb-Sr isochrons of around 110-130 my in the northern parts of several lower and middle Pennine nappes, some 50-100 km east and west of the Geotraverse may indicate tectonic events also along the northern margin of the middle Pennine platforms, although these data are not yet completely understood. Coeval clastic deposits in the north-Pennine Valais trough are widespread, but have been considered in the light of transform movements parallel to the E-W trend of the basin (HOMEWOOD 1977).

In the Piemont ocean late Cretaceous terrigenous flysch sequences (Simme and Gets nappes) overlie tectonized turbidites and olistostromes ("complexe de base"). Other extensive parts of the south-Pennine ocean, however, show fairly tranquil conditions with thick sequences of basinal lime-mud turbidites in monotonous and fairly constant facies along the trend of the Alpine belt (CARON et al., in preparation).

Meso-Alpine events

From late Cretaceous to late Eocene times, nearly all oceanic crust and lithosphere must have disappeared and the mutual approach of the European and the African/Apulian blocks culminated in continental collision. This Meso-Alpine orogeny is the main deformative and metamorphic event recorded along the section of the Geotraverse. During the middle to late Eocene, flysch sedimentation and redeposition of allochthonous complexes in sedimentary melanges (Wildflysch) encroached successively over the Pennine platform areas and onto the northern Ultrahelvetic-Helvetic margin heralding the overthrusting of the allochthonous units. Decollement of sedimentary cover nappes (Préalpes médianes, Simme s.l.) and development and refolding of the Pennine basement nappes below the overthrust Austroalpine units occurred during this phase. Temperatures in the more deeply buried rocks rose and subjected the Pennine nappes to medium pressure greenschist-amphibolite facies, overprinting Eo-Alpine parageneses in what has become known as the Lepontinic metamorphic phase (detailed discussion see in FREY et al., this volume). Some andesitic volcanism may have been associated with these events as indicated by the presence of andesitic detritus in the Taveyannaz Sandstone of the Helvetic realm. The source area of these volcanic debris is still debated but most probably has been located in the southern part of the Meso-Alps

(Hsü 1979) where small Eocene to early Oligocene granitoid intrusions are found (Bergell, Biella, Traversella).

Neo-Alpine events

At the end of the early Oligocene, the allochthonous units (Ultrahelvetic to Austroalpine nappes) reached as far north as the northern Aar Massif (Milnes & Pfiffner 1977) across the still undeformed Helvetic realm and the depocenters moved to the shallow seas and alluvial plains of the Alpine foreland (lower depositional cycle of north-Alpine Molasse). As a consequence of the late Eocene/early Oligocene events, the sequences now composing the Helvetic nappes were covered by a pile of nappes of Ultrahelvetic to Austroalpine provenance and most probably the very low to greenschist-grade metamorphism observed in the Helvetic sediments is connected with this event. Uplift followed the formation of nappes with a certain delay: from the late Oligocene onwards the entire block north of the Insubric fault was uplifted at rates reaching 2-3 mm/y (Werner et al. 1976). Erosion of the exposed Austroalpine and Pennine units is documented by the clastic content of the late Oligocene/early Miocene molasse conglomerates north of the Alps and of the coeval deep-sea fan deposits in the south (south-Alpine "Molasse"). The points Basel and Chiasso were about 300 km apart at that time.

During the late Oligocene and Miocene, new segments were added to the Alpine edifice: The basement of the Helvetic nappes was eliminated by subduction (with the Tavetsch "Massif" as only exposed remnant) and the Helvetic sediments were thrust together with their allochthonous cover to the north over the Aar Massif. A low grade regional metamorphism associated with this Neo-Alpine event is documented in the deeper Helvetic units and in the autochthonous to "parautochthonous" cover of the Aar Massif (Infrahelvetic units). Boulders of Helvetic sediments appear in the uppermost conglomerates of the second, middle Miocene, regressive depositional cycle of the Molasse north of the Alps.

Continued deformation in the lower levels of the massif is probably connected with decollement and thrusting in the Jura mountains (Laubscher 1973; Hsü 1979). Stratigraphic data indicate a late Miocene or early Pliocene age for the latter. The main deformation of the Southern Alps occurred also in a time interval between the middle and the topmost Miocene (Messinian).

9. Synopsis

Several characteristic features of the Geotraverse Basel-Chiasso are depicted in Figure 6, with special emphasis on geophysical signatures. The synoptic representation relates the geologic structures as visible at the earth's surface to deep structure as determined by seismic techniques, along with geodynamic manifestations such as crustal movements. The following discussion will focus on the manifold interrelations of the different aspects in individual sections along the Geotraverse.

The region near Basel, the morphological southern border of the *Rhinegraben*, is characterized by fault tectonics and a relatively thin crust. However, several features, like the seismicity pattern, lithospheric structure, temperature field, and recent vertical crustal movements indicate that the Rhinegraben might continue at depth, well beyond its morphological boundary at the surface in the region of Basel, much further to the SSW, into the area of Lausanne (MUELLER & RYBACH 1979).

In the profile of the Geotraverse the *Jura mountains* and also the *Molasse basin* are underlain by a crystalline crust of more or less constant thickness: the top of the crystalline basement (see also Fig. 3) and the base of the crust (= Moho) run essentially parallel, along with increasingly more negative gravity (Bouguer) anomalies. Significant vertical crustal movements are absent, as well as excess horizontal compressive stress. The geothermal field is characterized by a decrease of the geothermal gradient from Basel to Luzern (see RYBACH & BODMER, this volume).

The northern limit of the Subalpine (overthrusted) Molasse near Luzern marks a change in several decisive parameters: vertical uplift reaches a significant level as well as the excess horizontal compressive stress ($\Delta\sigma_H$); in going further south (the area of the *Helvetic nappes* which have overridden the sediments of the Molasse basin by several tens of kilometers) the uplift rates and also $\Delta\sigma_H$ increase, accompanied by negative isostatic anomalies (KAHLE et al. 1976*b*). The northern border of the *Aar Massif* (an external "massif", see the discussion in chapter 2 of this review) coincides with a zone of tectonic accidents and of increased seismicity (PAVONI 1977); the crustal structure below the Aar Massif shows several complications (MUELLER et al., this volume).

The gravity minimum (Bouguer anomaly − 150 mgal), caused by the "root" of the Alps, is located near the Rhine-Rhone Line (*R.R.L.* in Fig. 6) and not below the highest peaks of the Alps. The gravity increase further to the south which is due to the edge effect to the Ivrea body. The realm between the Rhine-Rhone Line and the Insubric Line (*I.L.*), the *Lepontine area*, is a most peculiar feature along the Geotraverse. The coincidence of maximum crustal thickness (>50 km), maximum $\Delta\sigma_H$ (>20 MPa), maximum uplift rates (~1.5 mm/y), all these clearly to the south of the watershed of the Alpine chain, is characteristic of this area. The seismic stratification (low-velocity layers, also in the lower crust) indicates a possible interfingering of crustal layers ("northern" crust intercalated with "southern" crust), the latter most probably including subducted remnants of the Helvetic basement (Tavetsch "Massif"). The root of the Alps is asymmetric; the original crustal thickness in the Lepontine area must have been even larger than 50 km since the block north of the Insubric Line has been vertically uplifted (relative to the Southern Alps) and eroded by about 20-25 km (BÜCHI & TRÜMPY 1976; see also WERNER et al. 1976).

The movement of the Lepontine realm apparently had substantial horizontal components as well; the rotation of this block as reported by HELLER (this volume) must have occurred after cooling down to the Curie temperature (~18 my ago; see WERNER, this volume). This implies that the Lepontine area acted as a block performing "individual" movements and did not react as a segment of the African plate (according to CHANNEL et al. 1979 the rotation of the Adriatic Promontory of the African plate terminated already in the Eocene).

South of the Insubric Line normal crustal thickness is successively attained while significant uplift and horizontal compressive overpressure ($\Delta\sigma_H$) still prevail in the *Southern Alps*. The gravity field is still influenced by edge effects of the Ivrea body.

The selection of the Geotraverse Basel-Chiasso to transsect several contrasting geologic/tectonic units has further implications: it coincides with the direction of maximum crustal shortening during the geodynamic development in the past and also corresponds to the direction of today's maximum horizontal compression in the upper crust. The complex interplay of uplift and isostatic anomalies, seismicity and stress field, temperature field and lithospheric structure is clearly indicative of the vivid present and past geodynamics of the Alpine system.

Acknowledgment

We thank all our colleagues who have actively contributed to the activities of the Working Group "Geotraverse Basel-Chiasso" of the Swiss National Committee for the IGP over the five years of cooperation. Special thanks are due to Zsolt Fejér (Zürich) for his continuous engagement in designing several versions of many figures concerning the Geotraverse Basel-Chiasso.

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