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CRUSTAL SHORTENING IN THE ALPINE OROGEN: RESULTS FROM DEEP SEISMIC REFLECTION PROFILING IN THE EASTERN SWISS ALPS, LINE NFP 20-EAST

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Abstract. The deep crustal seismic line NFP 20-EAST crosses almost the entire Swiss Alps. Despite the complex geometry of the well-exposed nappe structure and the considerable axial plunge of some of the units, the Vibroseis survey yielded coherent reflections from several individually identifiable nappe contacts. In the northern part of the survey the Vibroseis data closely match the internal structure of the Helvetic nappes and the underlying autochthonous-parautochthonous Mesozoic sediments. On the northern flank of the Aar massif, an external basement uplift, these Mesozoic sediments seem to rise from a depth of approximately 7-8 km below sea level to the surface in a series of steps which is interpreted to represent crustal shortening achieved by a combination of folding and thrusting. In the southern part of the survey it was possible to image a number of thin slivers of Mesozoic carbonates pinched between slabs of Penninic basement nappes as well as nappe contacts between lithologically contrasting units. In addition, it seems that the Insubric fault zone, which marks the contact between the Penninic zone and the Southern Alps and which outcrops about 30 km to the south of the survey, shows up as steeply north dipping reflections. The lower European crust in the northern part of the survey is relatively transparent as opposed to the Adriatic lower crust, whose reflective nature may stem from shear zones associated with Mesozoic crustal stretching. The base of both the European and Adriatic crust coincides with a 1-s-thick band of laterally discontinuous reflections. This reflection Moho drops to greater depths going from the north toward the center of the Alpine chain, where it disappears with a steep southerly dip. The Moho reappears as a reflection band farther south. This Moho gap is situated above the lithospheric root and may be caused by perturbations related to subduction of lower crustal material. The crustal-scale structure obtained from the Vibroseis data may be interpreted as a continent-continent collision with wedge-shaped indentation of a piece of Adriatic crust into the European crust

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and vertical escape of the material in the core of the orogen along steeply dipping faults.

INTRODUCTION

This paper presents results of a crustal seismic reflection survey across the Alps of eastern Switzerland. The seismic line NFP 20-EAST is part of the Swiss National Research Program 20 (NFP 20), which includes three seismic reflection profiles with a total length of about 350 km. The survey is supported by other geophysical and geologic projects aimed at elucidating the crustal structure of Switzerland. NFP 20-EAST extends through the thin-skinned and thick-skinned compressional structures of the Helvetic zone in the northern part of the Alps and the Penninic zone in the interior of the Alps (Figures 1 and 2). It transects deep portions of metamorphic zones exposed due to extensive uplift and erosion that started in the Tertiary and persists today. The line transects major Alpine structures that are constrained by surface data. These Alpine structures include shallow to moderately dipping thrust faults that juxtapose rocks of very different lithologies and physical characters; some rocks are highly anisotropic due to extensive deformation at elevated temperatures. Although the north-south line NFP 20-EAST is more or less perpendicular to the regional trend of Alpine geology, some structures possess a considerable dip toward the east. By using downdip projection there is a direct geometric tie between exposed and seismically imaged structures.

GEOLOGIC FRAMEWORK

The Swiss Alps are divisible into five major geologic units defined by the peculiarities of their Mesozoic-Cenozoic sedimentary sequences. From north to south they are (Figure 1) the Molasse, the Helvetic zone (including the basement uplift of the Aar massif), the Penninic zone, the Austroalpine nappes, and the Southern Alps.

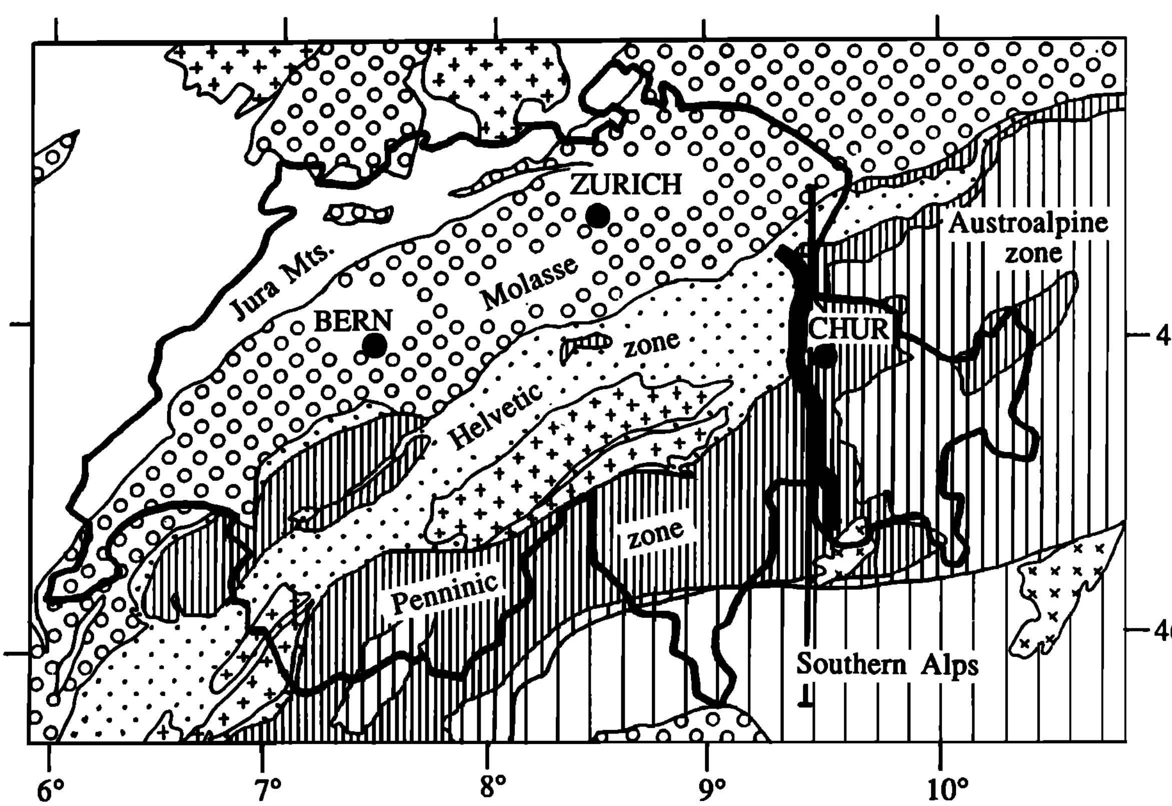


Fig. 1. Simplified geologic map of Switzerland showing trace of NFP 20-EAST (heavy line) and trace of geologic cross section of Figures 5-7 (thin line).

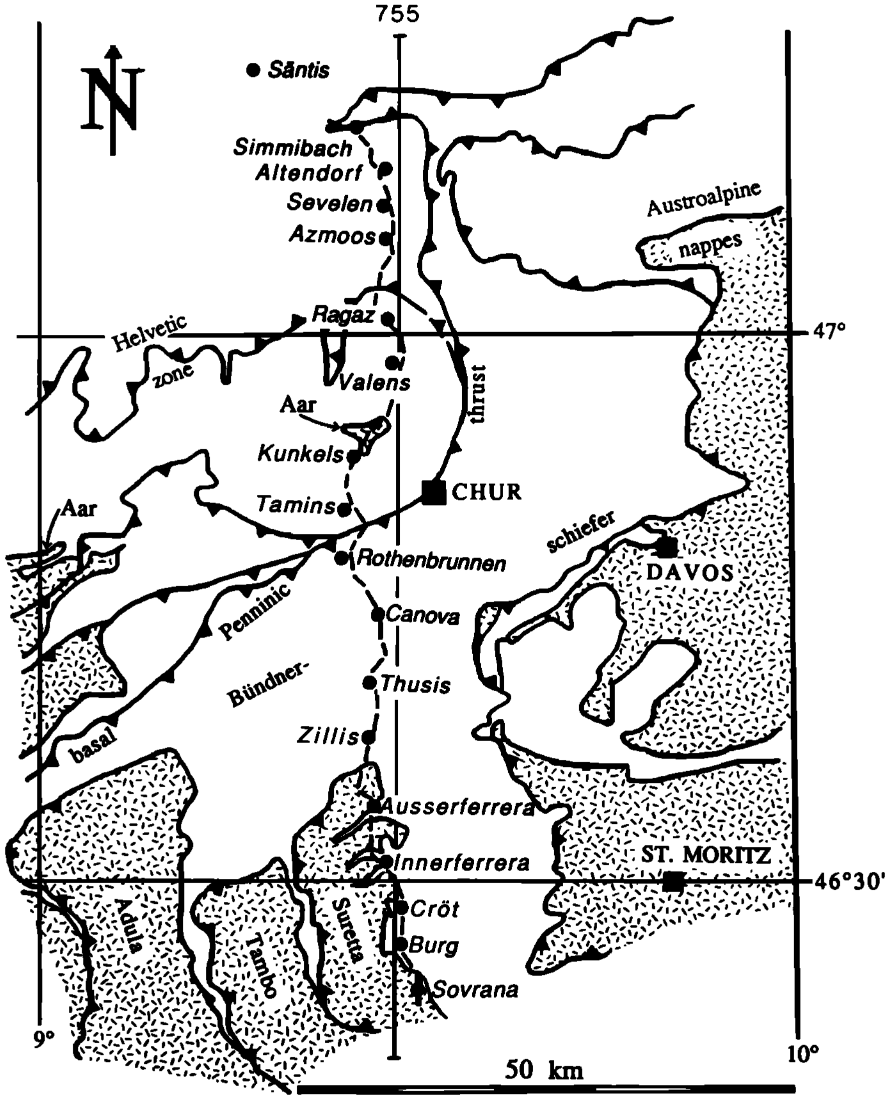


Fig. 2. Detailed map of NFP 20-EAST (dashed line) with shot points (solid circles). Traces of the geologic cross sections follow km 755 of the Swiss National grid net. Solid squares are towns.

The Molasse comprises Oligocene to Miocene strata that were deposited on slightly tilted Mesozoic-Eocene strata. The latter represent the autochthonous cover of the European crystalline basement that outcrops in the Black Forest and Bohemian massif of southern Germany. Molasse sediments are considered to be late synorogenic. In the south they are deformed; they were tilted, detached from their substratum, and now form an imbricate fan.

In the Helvetic zone, Mesozoic-Oliogocene sediments overlie a Variscan basement. Within this basement three major units are recognized. The oldest unit consists of pre-Variscan polymetamorphic gneisses, metasediments, and schists with a steeply dipping foliation. These rocks are intruded by a series of late-Variscan, 330- to 270-Ma-old granitoids. Finally, a Permo-Carboniferous volcaniclastic sequence overlies (or is locally intruded by) the granitoids; these volcaniclastic rocks were in part tightly folded by the Variscan orogeny and now outcrop in narrow steeply dipping zones. The cover sequence starts with thin epicontinental sediments including dolomites of Triassic age, followed by Jurassic to Eocene platform carbonates and locally an Eocene-Oligocene flysch. In Eocene to Miocene times, cover sediments were in part detached from their basement, compressed, and thrust northward to form the Helvetic nappes. Beneath the Helvetic nappes compression led to a thick-skinned fold-and-thrust belt, cored by the Aar massif basement uplift. Alpine metamorphism is anchizonal in the north and epizonal in the south.

In the Penninic zone, Mesozoic-Eocene sediments overlie a Variscan basement similar to that of the Helvetic zone. Unlike in the latter, however, extensive Alpine overprinting resulted in a gently dipping foliation. The cover sequence commences with epicontinental sediments (dolomites and limestones) of Triassic age. From the Jurassic onward three main realms representing different parts of the subsiding basin have been distinguished. In the more external North Penninic basin, Jurassic to Early Cretaceous sediments mainly comprise a monotonous turbiditic sequence of shales and arenites (the so-called Bündnerschiefer), which grades into a Late Cretaceous to Eocene flysch sequence. Locally, the Jurassic Bündnerschiefer contain slivers of ophiolitic material (prasinites, in part gabbroic, and serpentinites) and massive limestones. In the more internal South Penninic basin, hemipelagic and pelagic sediments of Jurassic and Cretaceous age overlie ophiolitic basement. The Penninic nappes made up of oceanic basement and sediments are already largely eroded in this transect, and NFP 20-EAST crosses below them.

In the mid-Penninic rise (Briançonnais) between the North and South Penninic basins, alkali ash-fall tuffs interlayered with middle Triassic carbonates can be compared to similar rocks in the Western Alps that are associated with faulting in the subsiding basin. Steep scarp breccias with unconformities of up to 45° at their base are of Jurassic to Early Cretaceous ge. They occur at the edge of a carbonate platform and indicate dominant transtensional strike-slip tectonic activity, although locally transpression has also occurred. Mesozoic thinning of continental crust is indicated by volcanic rocks (prasinites, gabbros, serpentinites, and glaucophane schists) intercalated in the Bündnerschiefer, by substantial subsidence in the South Penninic basin, and by the formation of a passive continental margin in the neighboring Austroalpine domain. In the Southern Alps, synsedimentary normal faulting in the Early Jurassic was followed by a more evenly distributed subsidence and the deposition of a pelagic sequence.

Compression in the Penninic zone may have started in the Cretaceous which associated high-pressure Alpine metamorphism. The nappe structures as seen today comprise a stack of basement flakes separated by thin slivers of sedimentary rocks. In some instances, the latter represent the lowermost cover of individual flakes. For the most part, however, cover sediments were stripped off their crystalline basement and now form a stack of internally complex nappes several kilometers thick. In the NFP 20-EAST transect the basement flakes occur mainly in the south and the detached sediments in the north (Figure 2). Basement flakes include, from top to bottom, the Suretta nappe, which suffered extensive internal thrusting and folding, the Tambo and Adula nappes, in which the frontal antiforms are particularly deformed, and the Simano nappe that outcrops 35 km west of the line. Tertiary intrusions (Novate granite, 27 Ma, and Bergell granodiorite, 30 Ma) situated just south of NFP 20-EAST crosscut the nappe structures.

The youngest sediments within the Penninic zone were deposited in the Early Eocene and this deposition was at some localities coeval with the syntectonic growth of glaucophane (50 Ma formation age of glaucophane in the Triassic cover of the Suretta nappe [cf. Hurford et al., 1989]). Alpine metamorphism in the Penninic zone along this transect is lower epizonal in the north and upper epizonal in the south. The boundary between epizone and amphibolite facies regional metamorphism passes just south and east of the transect and crosscuts nappe boundaries.

The Mesozoic sediments of the Austroalpine nappes and the Southern Alps were deposited on the stretched passive margin of the Periadriatic promontory in the south Tethys Ocean. The cover overlies Variscan basement affected by Alpine deformation. The NFP 20-EAST transect passes "beneath" the Austroalpine nappes, which were eroded from the Penninic and Helvetic zones in Oligocene and Miocene times. The Southern Alps lie to the south of the seismic profile and are separated from the Penninic zone by the Insubric Line, a major lineament involving combined vertical and dextral strike-slip movements in Oligocene to Miocene times.

DATA AQUISITION AND PROCESSING

The parameters used for acquiring line NFP 20-EAST are listed in Table 1. In addition to the Vibroseis profile, which was designed to yield high-resolution information on the upper crust, a deeper-penetrating explosion data set (near vertical reflection) was collected along the same line [Pfiffner et al., 1988]. Generally speaking, the two data sets give rather comparable results. Indeed, closer inspection confirms that within the upper crust the highfold Vibroseis stack gives finer details and better continuity, whereas the higher-energy explosion data yield more information from the deep structures.

Vibroseis source and receiver intervals were set at 40/80 m, providing closely spaced 20/40 m subsurface coverage. The high ambient noise level associated with the densely populated regions made it difficult to record weak signals from deep crustal levels. Testing with various sweep lengths it was found that super-long Vibroseis sweeps (60 s) yielded the best energy penetration. In addition, recordings were made only during the quiter nighttime hours. The recording conditions and in particular, source coupling varied considerably because of limited access across the rugged mountains and through the villages. To minimize these problems, a 240 channel receiver array spread over 20 km was employed to undershoot the smaller-scale near-surface "anomalies."

Using different hardware and software configurations, processing was carried out simultaneously at two data centers, one at the Eidgenössische Technische Hochschule in Zurich [Valasek et al., 1990] and the other at the University of Lausanne [DuBois et al., 1990b]. The processing sequences adopted by the two groups resulted in various versions of the stacked seismic section, each highlighting different aspects of the data. The principal processing sequences used to produce the seismic sections described in this paper are listed in Tables 2 and 3.

The structural complexity of the Alps strongly influenced some of the conventional data processing steps such as velocity analysis and statics. Improved stacks relied heavily on residual statics to resolve time delays not properly accounted for by

TABLE 1. Acquisition Parameters for Vibroseis Line NFP 20-EAST

	Parameters used
Source	
Source type	Vibroseis
Number of vibrators (weight 15 tons)	5(+1)
Sweep length	60 s
Frequency range	8 - 48 Hz
Total Recording length	64 s
Vibration point spacing	40 m
Number of vibrations per location	2
Recording	uncorrelated, unsummed
Receiver	
Recording system	Sercel 348
Sample interval	4 ms
Number of receiver channels	240
Receiver group spacing	80 m
Number of geophones per group	24
Spread configuration	symmetric split-spread
Total spread length	19.4 km
Coverage	120
Working hours	20:00-05:00 h

TABLE 2. Processing Sequences for Vibroseis Line NFP 20-EAST by Zurich Processing Center

Processing Steps	Northern Half	Southern Half	Complete Section
Demultiplex and gain recovery	+	+	+
Vibroseis whitening (AGC 500 ms)	+	+	+
Vibroseis correlation	+	+	+
Vertical stack (2- and 4-fold)	-	+	+
Crooked line geometry	+	+	+
Sort (CMP spacing)	20 and 40 m	40 m	40 m
Resample 4 to 8 ms	+	+	+
Trace editing	+	+	+
Trace equalization	600 ms	1000 ms	1000 ms
Spectral balancing	-	-	-
Time-variant predictive decon	+	-	N
(Gap 32 ms, Operator 256 ms)	-	-	-
Band pass filtering	10-44 Hz	10-40 Hz	10-40 Hz
Elevation statics (floating datum)	+	+	+
Normal moveout correction NMO	+	+	+
Mute	+	+	+
Surface consistent residual statics	1 cycle	2 cycles	1 cycle
CMP consistent residual statics	1 cycle	2 cycles	1 cycle
CMP stack (offset range)	full range	full range	-4.5 to 4.5 km
Elevation statics (700 m datum)	+	+	+
Predictive deconvolution	+	-	S
Band pass filter 0-6 s	14-44 Hz	-	16-40 Hz
6-9 s	-	-	14-30 Hz
9-20 s	-	-	10-20 Hz
Scaling (AGC)	1000 ms	2000 ms	10000 ms
Horizontal sum (2-fold)	+	-	-
Coherency filter	+	+	+

"+" indicates that the processing step was applied.
"-" indicates that the step was not applied.
"N" indicates process was applied only for the northern half.
"S" indicates process was applied only for the southern half.

standard normal moveout corrections. Partial pre-stack migration (dip moveout, DMO) allowed the stacking of both dipping and horizontal reflectors with their correct velocities. Due to the large field spread and high folding coverage, different offset partial stacks were made. In particular, near-offset stacks improved the stack quality. Restriction of a narrow range of offsets avoided destructive stacking of traces with uncorrectable long-wavelength "statics" developed in laterally varying velocity anomalies. Coherency filtering was used as a final means of post-stack signal-to-noise ratio improvement.

SEISMIC SECTIONS

Unmigrated seismic sections are displayed in Plates 1, 2, 5, and 6. Line drawings, displayed in Plates 3 and 4, were obtained in two steps: In a first step, reflections extending over a minimum of five traces (200 m) in the northern half (Plate 3) and 10 traces (400 m) in the southern half (Plate 4) were picked. Amplitudes of the reflections were not solely used as a selective criterion because many of the faint reflections visible in the presented seismic section appeared to be stronger and laterally more continuous in near- or intermediate-offset stacks. In a second step, only those re-

TABLE 3. Processing Sequences for Vibroseis Line NFP 20-EAST (Northern Half) by Lausanne Processing Center GRANSIR.

Processing Steps	Parameters
Resample	4 to 8 ms
Scaling	Spherical divergence
Time variant zero-phase deconvolution	
Gate 1	10-44 Hz 0-6 s
Gate 2	10-40 Hz 6-9 s
Elevation statics	700 m datum
Mute	
Partial normal moveout corrections	
Dip moveout correction (DMO)	
Residual normal moveout correction	
Surface consistent residual statics	2 cycles
CMP stack	
Band pass filter	16-40 Hz
Scaling	AGC
Gate 1	600 ms 0 - 1.5 s
Gate 2	2000 ms 1.5 - 9 s
Resample	8 to 4 ms
Coherency filter	

For processing up to CMP sort see Table 2. Trace interval 40 m.

flections with twice the minimum lengths discussed above were selected. The resulting line drawings are shown in Figures 3 and 4. We feel that these remaining reflections are still representative for the general aspect of the reflectivity. It is on these line drawings shown in Figures 3 and 4 that the outline of the geologic interpretation is given. The data are presented in two sections, covering the more detailed shallow data and one section covering the entire line down to the deepest data.

Northern Half of the Section

The northern half of the section shown in Plates 1, 3, and 5 extends over the

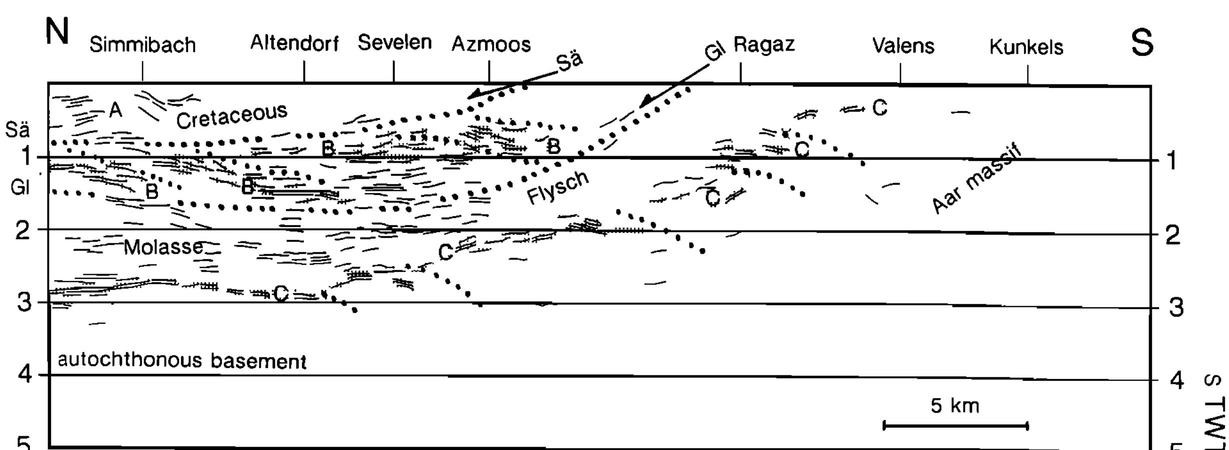
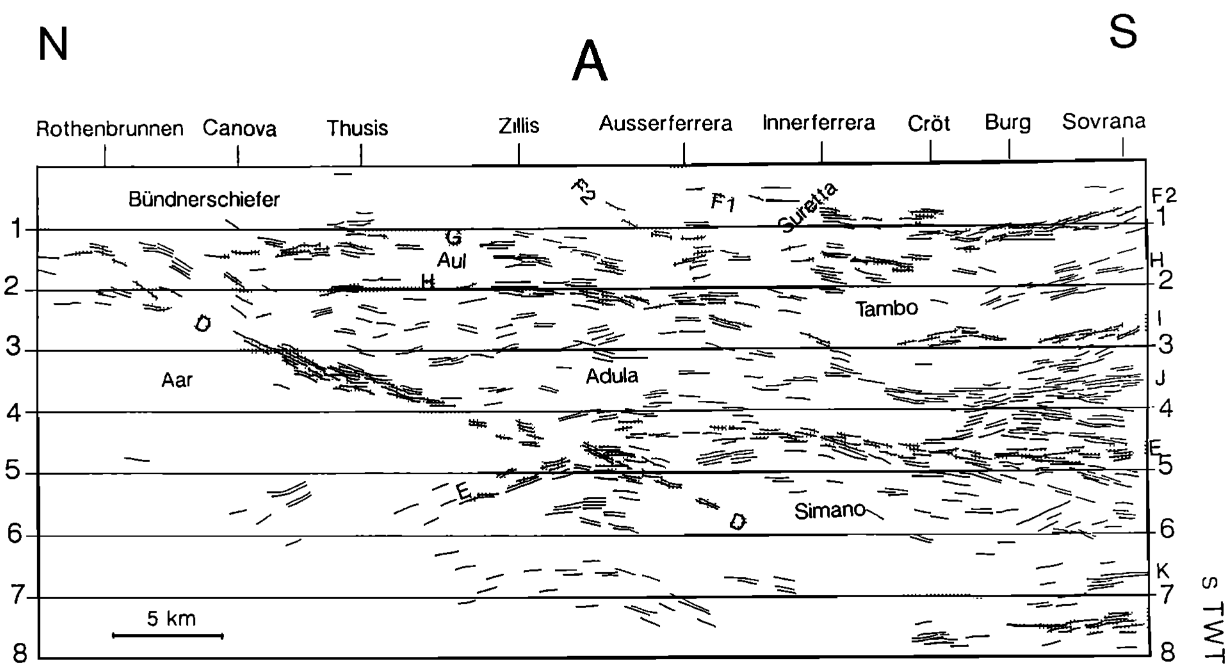


Fig. 3. Line drawing with simple geologic interpretation of the northern half of NFP 20-EAST (unmigrated time section). Only reflections extending continuously over a minimum length of 10 stations (400 m) were picked. Arrows denote major thrust faults. Sä and Gl; Säntis and Glarus thrusts; stippled areas, Triassic-Jurassic carbonates.



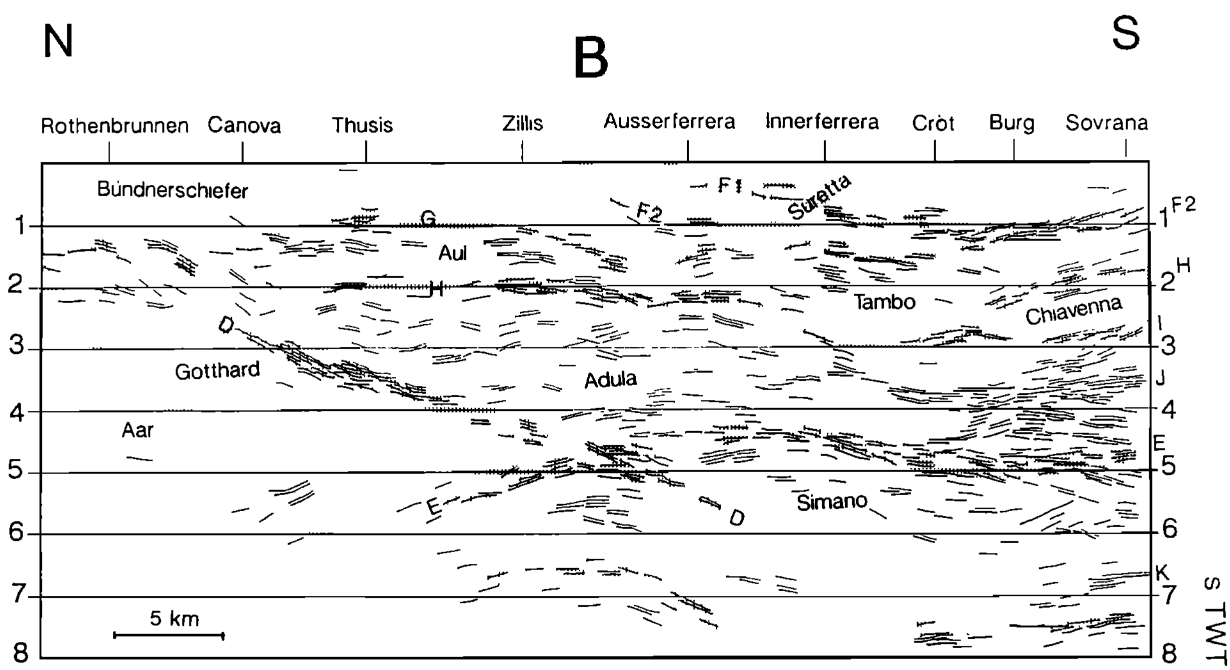


Fig. 4. Line drawing with three possible geologic interpretations (A, B, and C) of the southern half of NFP 20-EAST (unmigrated time section). Only reflections extending continuously over a minimum length of 20 stations (800 m) were picked. Stippled areas are major nappe contacts juxtaposing carbonates and basement or Bündnerschiefer.

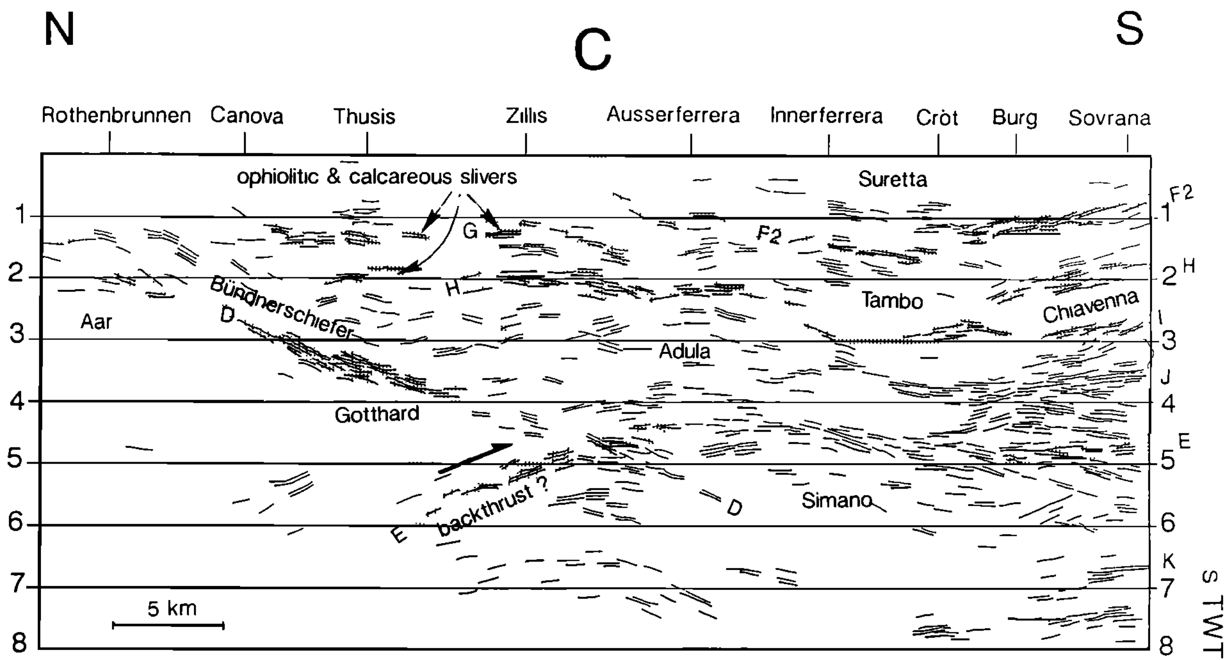


Fig. 4. (continued)

Helvetic zone and covers the upper 5 s two-way travel time (TWT). The locations given on the section are shot points of the explosion seismology experiment shown in Figure 2 [cf. Pfiffner et al., 1988]. Plate 5 shows the section between Altendorf and Valens after DMO corrections.

Coherent reflections can be seen mainly between 0 and 3 s in the north; they degrade in strength toward the south. The most noticeable reflection zone (marked C in Plate 3) is situated at 2.8 s at the northernmost end. It is characterized by its high amplitude, double cyclic nature, and subhorizontal geometry and is accompanied by irregular, short reflections immediately beneath and above it. South of Sevelen this strong reflection begins to dip upward (see Plate 5) and then continues as discrete panels of progressively weaker reflections rising stepwise toward the south. Because these reflections are of particular importance for the geologic interpretation (as we will discuss below, they correspond to the northern flank of the Aar massif basement uplift), extra effort was put into the processing of this segment. The seismic section in Plate 5 shows the result of DMO processing, which enhanced the continuity of the dipping reflectors.

Between 1 and 1.6 s north of Simmibach a pattern of several south dipping reflections is notable (B in Plate 3). These events also show a double cyclic swing and high amplitudes. Beneath Altendorf their orientation changes from south dipping to horizontal and then ultimately to north dipping (see Plate 5). The transition from south dipping to horizontal likely results from a change in the recording direction from along the regional strike to more perpendicular to it (see Figure 2). The antiformal reflections (A in Plate 3) at less than 1 s north of Simmibach continue faintly southward to Sevelen and then fade off. The lower part of the section (below 3.3 s beneath Altendorf and below 1.5 s beneath Ragaz) is best described by its lack of strong, long-reaching reflections.

Southern Half of the Section

The southern half of the section, shown in Plates 2 and 4, extends over the Penninic zone and is reproduced down to 8 s two-way travel time. Strong reflections between 0 and 7 s are mainly south dipping in the north and north dipping in the southern portion, with several reflections crossing each other. A number of reflection groups can be distinguished.

The prominent reflection group, D in

Plate 4, starts beneath Rothenbrunnen at 1.3 s. It consists of an irregular, discontinuous band of reflections dipping to 5.5 s beneath Ausserferrera. At 5 s reflection, group D crosses north dipping reflection band E, similar to a bow tie reflection pattern often received from synformal structures.

Above the prominent south dipping reflection group D, there are several subhorizontal reflection groups that are composed of discontinuous multicyclic reflections. The topmost one, F1, appears between Ausserferrera and Innerferrera at 0.5 s and extends to Cröt, where it rejoins another group, F2, which is at 1.5 s beneath Innerferrera. From here, F2 rises to the north and the south. South of Canova, reflection group G at 1.2 s and H at 2 s can be followed southward, G to beneath Ausserferrera and H to the end of the section. H is characterized by its wavy appearance along the entire section. In addition to events E, F2, and H the southern end of the section is characterized by several high-amplitude, north dipping reflections (I at 2.7, J at 3.5, and K at 6.7 s), all of which are paralleled by numerous coherent but weaker events.

The Complete Section

Three deep reflection packages are observed on the seismic section of Plate 6 which contains the entire data set down to 20 s two-way travel time. These deep reflections are comparable to the explosion data set [Pfiffner et al., 1988]. The first package, marked L in Plate 6, comprises sparse, discontinuous, short reflections within a 3- to 5-s-wide zone extending from about 9 s beneath Sevelen to 10 s beneath Tamins.

The second package, M in Plate 6, is a highly reflective band with a duration of 1 s that dips southward from the northern end at 11 s to 15 s at its deepest point beneath Canova. Near the southern end of the section it reappears at 13-15 s. Steeply north dipping reflections appear from 8 (N1) to 14 s (N2) at the southern end of the section.

In several areas the reflection quality of deep reflections degrades. Examples are the area beneath the segment between shot points Sevelen and Ragaz, and the area beneath Tamins, both of which coincide also with dense population and industrialization. We feel therefore that this particular seismic character is not necessarily due to a change in the geologic structure but that it may relate to the more difficult recording environments.

GEOLOGIC INTERPRETATION

The crustal structure of this part of the Alps is fairly well known to a depth of 5-10 km due to the considerable axial plunge of the structures and the high topographic relief. This makes it possible to calibrate the reflections and refine and extend the interpretations. The three-dimensional geometry of potential reflectors such as basement-cover contacts has been analyzed using all the available surface data and projecting them to depth. These results are presented by Pfiffner et al. [1990]. For the deeper parts of the crust, refraction surveys show anomalous low-velocity bodies within the crust and place the Moho at a depth of around 40 km beneath Simmibach and at a maximum depth of around 50 km beneath Thusis (see Figure 7 and Müller et al., [1980]).

Shallow Structures in the North

Beneath the northern half of the line the strong reflections (C in Plate 3) around 3 s at the northern end are most likely related to the Mesozoic carbonates overlying crystalline basement rocks and overlying Tertiary sandstone-shale sequences of the Sub-Alpine Molasse (Figure 3). The basal contact of the Mesozoic is characterized by dolomites with high velocities of 7 km/s overlying crystalline basement with velocities around 6 km/s according to laboratory measurements [Sellami et al., 1990]. Late Jurassic limestones near the top of the Mesozoic carbonates possess higher velocities of around 6.5 km/s [Sellami et al., 1990] compared to the stacking velocities of around 5 km/s typical for the Tertiary. Borehole data from farther north suggest that the Mesozoic carbonates are situated at a depth of about 7 km beneath Simmibach. Toward the south the Mesozoic carbonates are known to rise to the surface until they outcrop just south of Valens. The basement rocks of the underlying Aar massif are exposed at the surface in the Vättis inlier situated just north of shot point Kunkels (Figure 2). The rise of this interface to the surface is related to the Aar massif basement uplift and implies a considerable amount of crustal shortening.

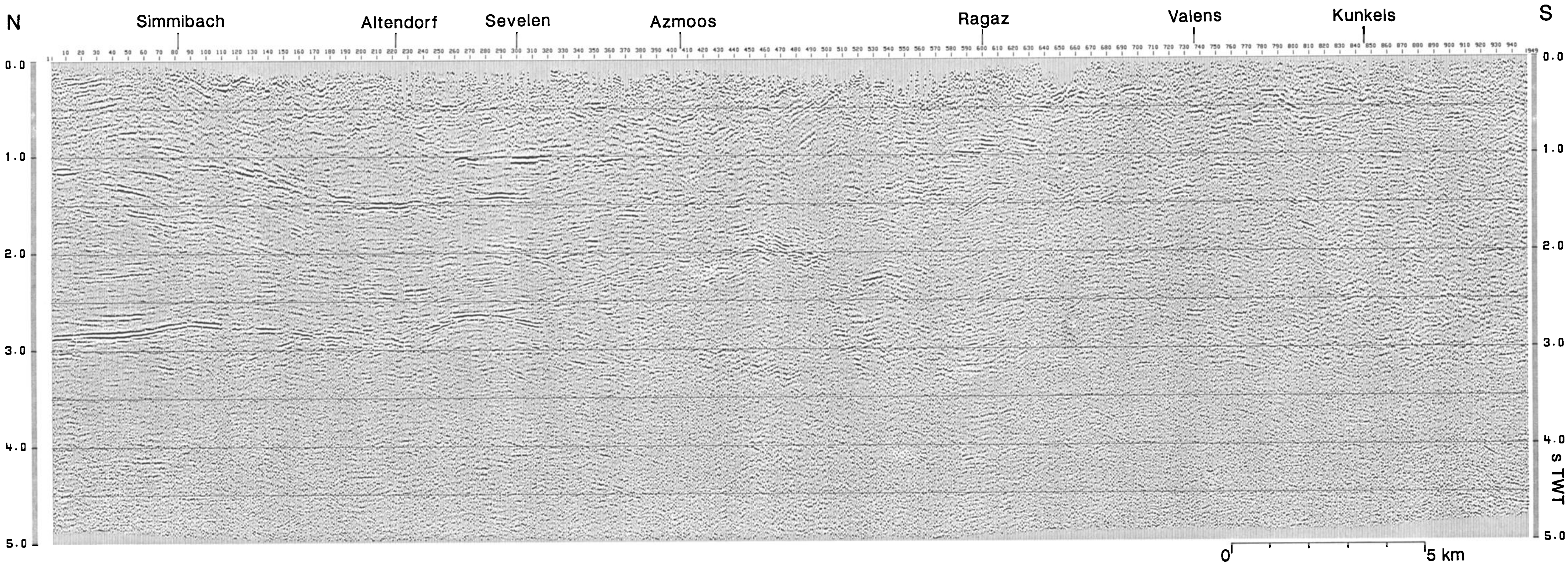


Plate 1. Unmigrated seismic line of the northern half of line NFP 20-EAST showing shallow reflections. See Figures 1 and 2 for location. Processing by Zurich processing center.

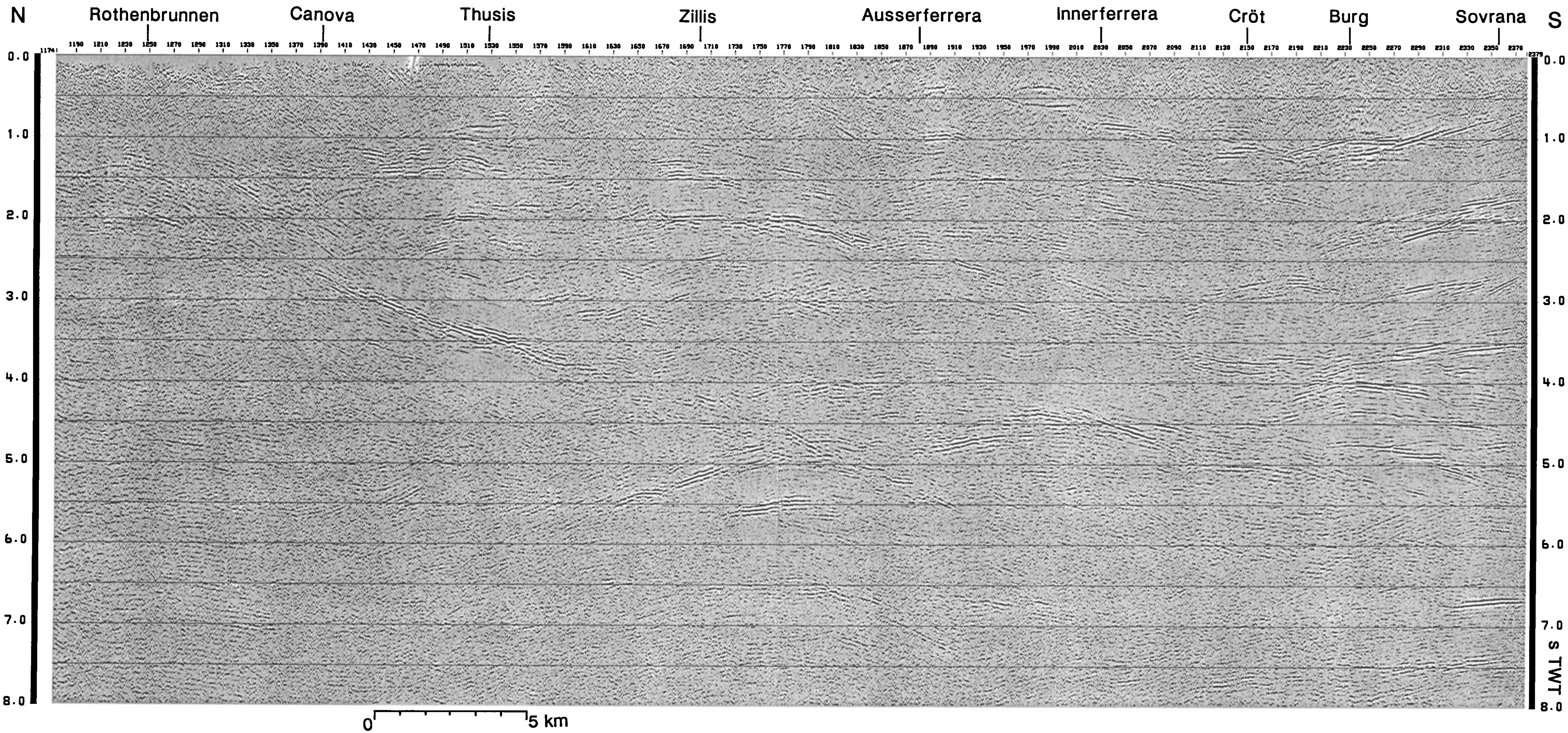


Plate 2. Unmigrated seismic line of the southern half of line NFP 20-EAST showing shallow reflections. See Figures 1 and 2 for location. Processing by Zurich processing center.

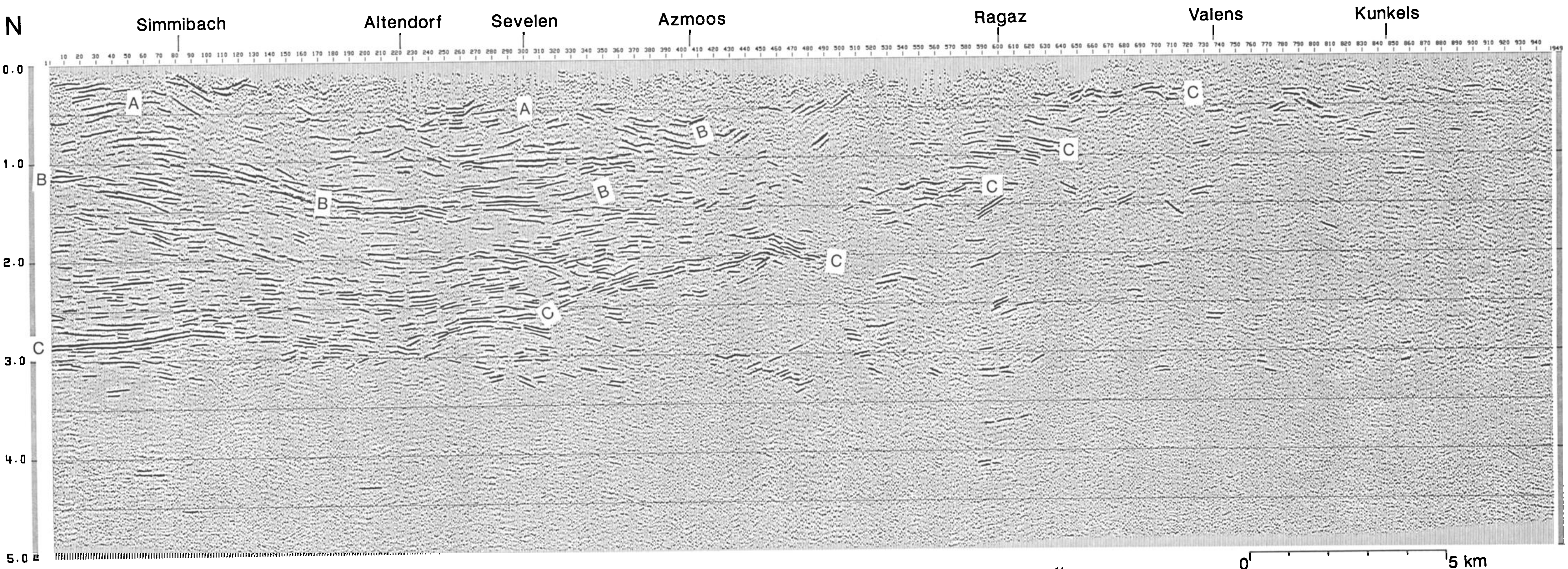


Plate 3. Interpreted seismic line of Plate 1 with reflections extending over a minimum length of 5 stations (200 m) picked. Reflection bands A, B, and C are discussed in text.

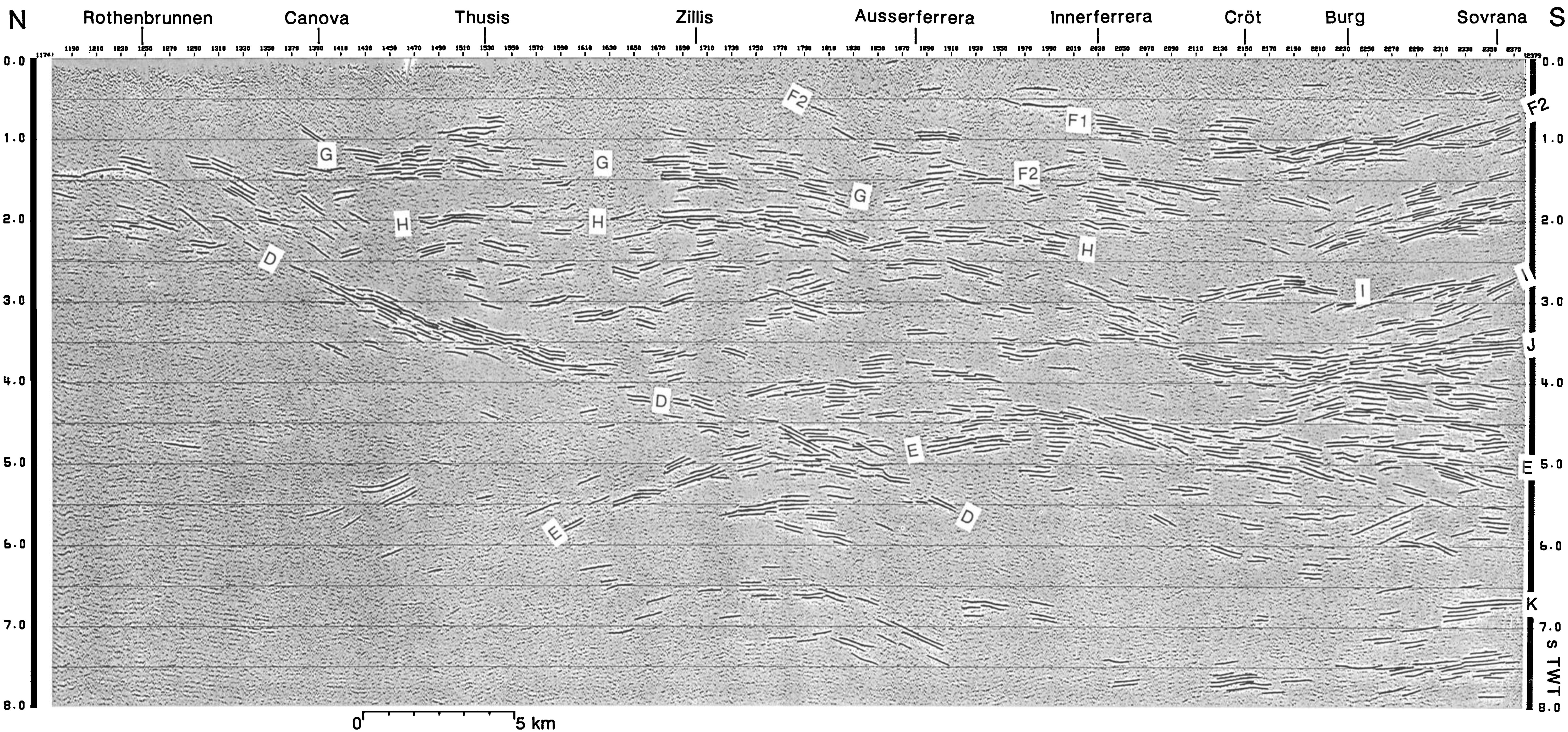


Plate 4. Interpreted seismic line of Plate 2 with reflections extending over a minimum length of 10 stations (400 m) picked. Reflection bands D through K are discussed in text.

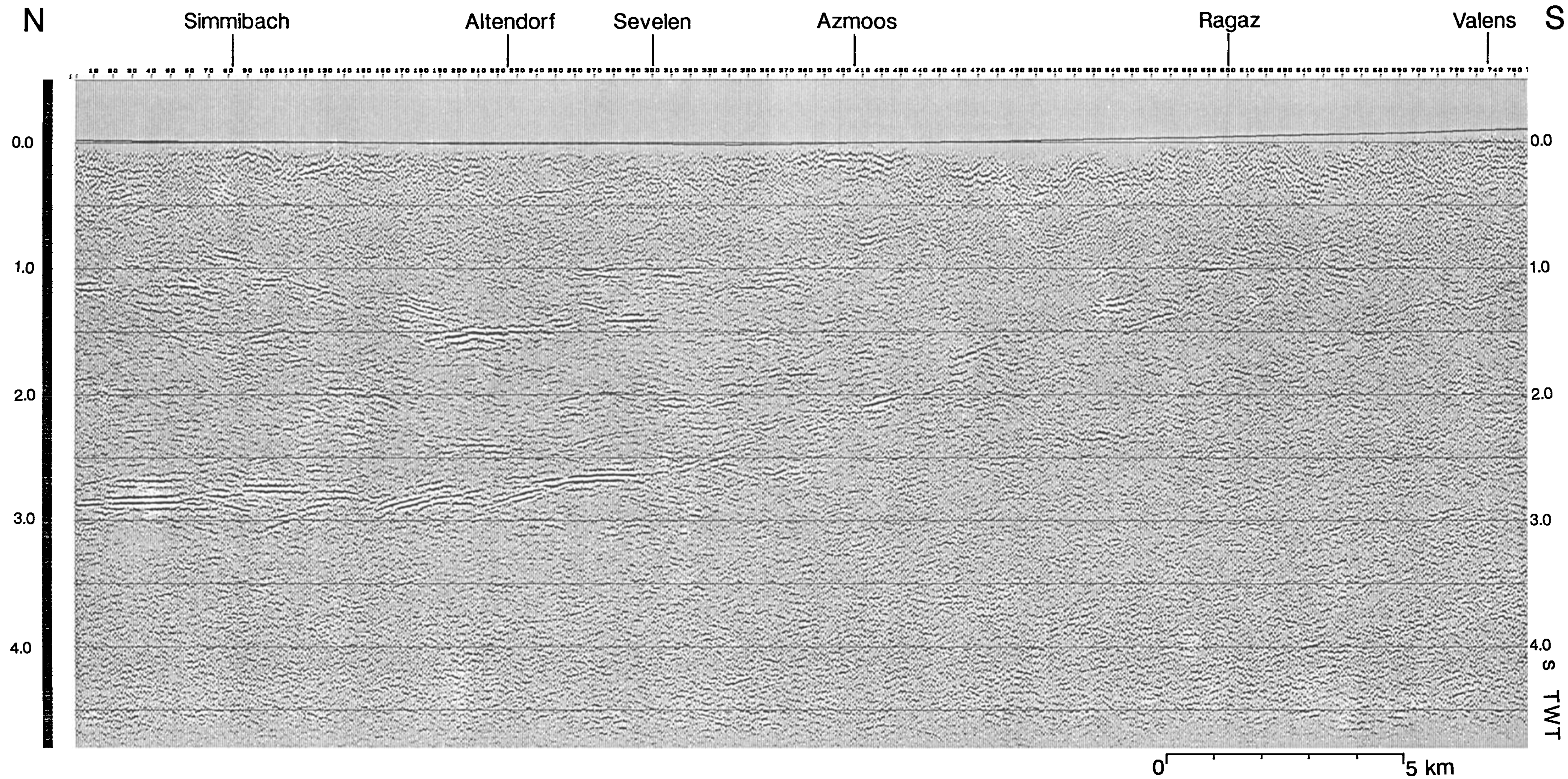


Plate 5. Unmigrated seismic line of NFP 20-EAST. Segment in the north showing shallow reflections after DMO corrections. Processing by Lausanne processing center GRANSIR.

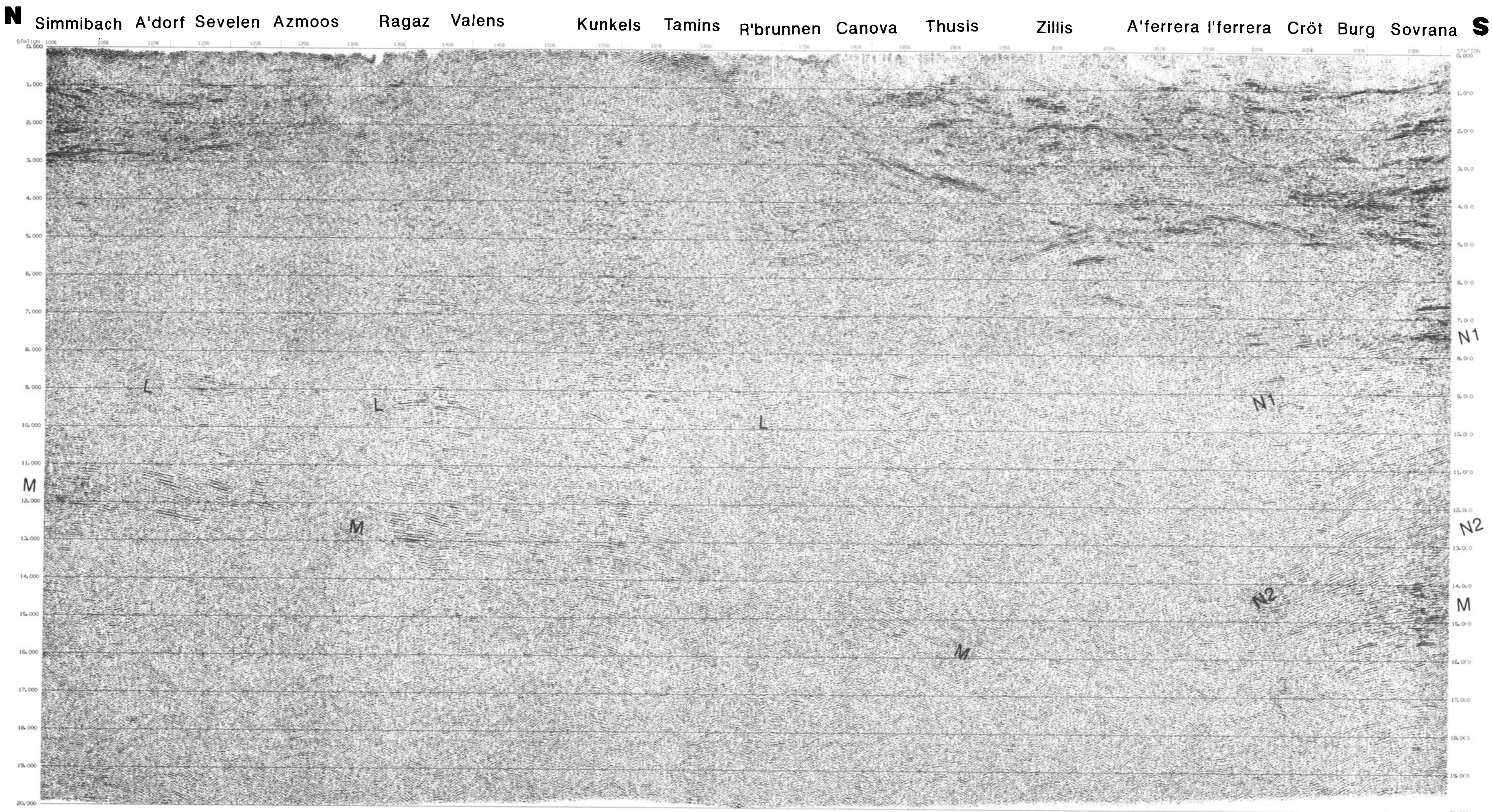


Plate 6. Unmigrated seismic line of NFP 20-EAST showing deeper reflections. Processing by Zurich processing center. Reflection bands L through N2 are discussed in text.

Several models describing the geometry of this uplift have been considered. A model in which the Aar massif would represent a ramp anticline with basement material overthrusting a slab of autochthonous Mesozoic rocks extending from Sevelen to the south at a depth equivalent to about 3 s was proposed by Pfiffner [1985]; it was intended to balance the shortening within the Sub-Alpine Molasse. Given the results from the immediate surroundings, such a slab should express itself seismically. However, the lack of reflections at the expected location suggests that a different structure must be sought. The more classic view, in which the rise of the top of the basement occurs in a relatively smooth way [cf. Heim, 1922, Plate XXVII; Milnes and Pfiffner, 1980; Trümpy, 1980], explains the north dipping reflections as seen in the seismic section of Plate 5, but it needs to be modified to account for the more stepwise rise indicated by the seismic data. The stepwise rise suggests the presence of relatively flat-lying slabs of Mesozoic carbonates, which can basically be achieved by recumbent folding, imbricate thrusting, or both. The solution to the problem presented in the geologic cross section in Figure 5 shows both reactions and tries to reproduce field observations made farther west. In these regions the Aar massif basement uplift reaches higher altitudes, exposing large-scale recumbent folding in the Windgällen area [cf. Funk et al., 1983; Pfiffner et al., 1990], thrusting on steeply dipping faults in the Frisal-Punteglias area, and a combination of folding and faulting in the Wetterhorn-Jungfrau area [e.g., Pfiffner et al., 1990].

Judging from the regional metamorphic grade (see Groshong et al. [1984] for a synoptic view along this cross section), it is plausible that the ductile folding beneath Valens changes further north to more brittle behavior comparable to the Wetterhorn-Jungfrau area.

The next group of reflections (B in Plate 3), extending from the northern end of the line (at 1.2 s) to Azmoos, can readily be correlated with the upper and lower interface of Jurassic limestones within the Lower Glarus Nappe complex of the Helvetic nappes. The Lower Glarus Nappe complex consists of a series of imbricate thrust sheets grading into folds south of Azmoos [Helbling, 1938; Pfiffner, 1981]. The interpretation given in the geologic cross section of Figure 5 is a down-plunge projection of the surface data outcropping some 10 km farther to the west which were adjusted to fit the observed reflection patterns. The reflections at around 1.4 s beneath Sevelen are interpreted as resulting from the interface between Early Jurassic limestones (Spitzmeilen and Sexmor formations) and Middle Jurassic shales and sandstones (Mols and Bommerstein formations).

The basal thrust of the Helvetic nappes, the famous Glarus Thrust (see Funk et al. [1983] for a historic outline), is expected immediately below these Jurassic rocks. It puts Permian red beds ("Verrucano") on top of Tertiary North-Helvetic Flysch with a displacement of about 50 km [Pfiffner, 1985] to the west of the line. It is likely that there is no Permian at the base of the Helvetic nappes because going east the basal detachment steps up from the Permian to a higher detachment level [see Pfiffner, 1981]. In the transect studied it possibly puts shaly Early Jurassic onto shaly-sandy Tertiary and might therefore not express itself seismically.

The few reflections (A in Plate 3) between 0 and 1.2 s obtained from the Cretaceous limestones and marls of the Upper Glarus Nappe complex or Säntis nappe are difficult to relate to the internal structure of this thrust sheet. The poorer quality of the near-surface data can be attributed to the fact that imaging such shallow structures was not the aim of the seismic experiment.

The Tertiary sediments underlying the Helvetic nappes show two types of reflection patterns: numerous short reflections in the north and a more or less transparent section in the south. The boundary between the reflective and the transparent domain is tentatively interpreted as the boundary between the Sub-Alpine Molasse and the North-Helvetic Flysch. The reflective nature of the Molasse can be attributed to its lithologic character: basal turbiditic fan deposits, overlain by fine-grained deposits (shales and shaly marls) grading into a sandy and conglomeratic sequence that characterize the Oligocene Lower Marine Molasse ("UMM" [Diem, 1986]). The repeated change from fine-grained to coarser-grained sediments at various scales may account for the generally reflective nature of the seismic section. In addition to the sedimentary intercalations, tectonic imbrications

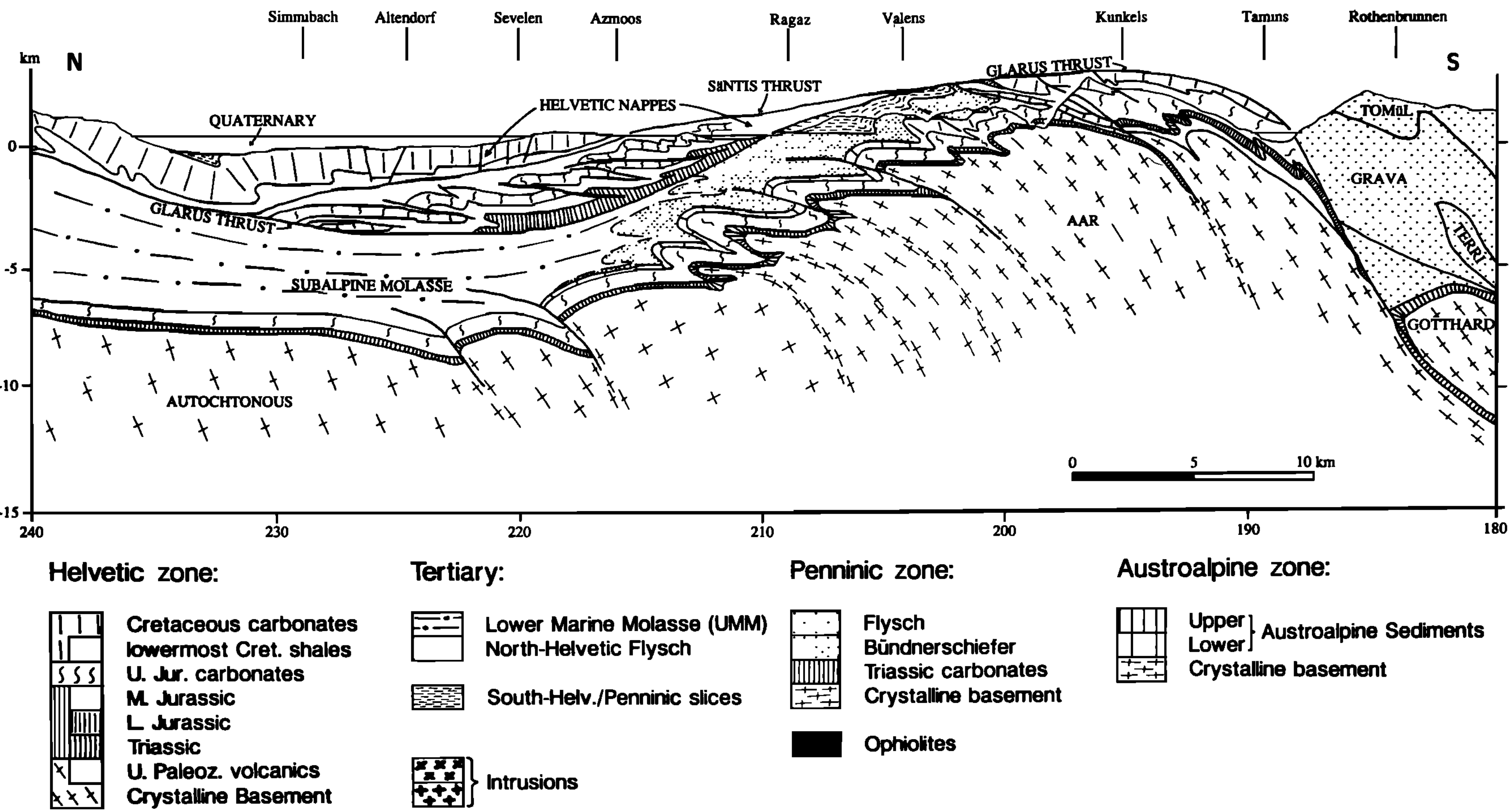


Fig. 5. Geologic cross section of the northern half of NFP 20-EAST based on the interpretation of the seismic data (Figure 3, Plates 1 and 5) and on regional structural style. The trace of the cross section is straight N-S following km 755 of the Swiss National Grid net (see Figure 2) and deviates from the seismic line at the northern end.

known to exist farther north at the surface are expected to cause repetitions in the section studied here. In contrast, the thick sequence of shales and sandstones of the North-Helvetic Flysch is intensively folded [Siegenthaler, 1974], which may explain the seismically more transparent nature of this domain. The transition from flysch to molasse-type sediments is gradual in lithology, age, and location of the depot center [e.g., Siegenthaler, 1974; Pfiffner, 1986] and therefore unlikely to produce a sharp change in the reflection pattern. In order to balance the shortened Sub-Alpine Molasse section situated farther north, a substantial amount of bedlength of Mesozoic carbonates has to be postulated in the area of the section studied. The structure of the contact between flysch and molasse in the geologic section of Figure 5 is intended to account for this. This point will be further discussed below.

Shallow Structures in the South

For the southern half of the seismic line the correlation between reflections and lithologic boundaries or faults is more difficult, and in some instances more than one interpretation is plausible. Hence three models (A, B, and C) are offered in Figure 4. The discussion will proceed from top to bottom.

Outcropping from south of Zillis to the southern end of the line is the Suretta nappe, a thrust sheet composed essentially of basement rocks topped by a thin cover of Mesozoic quartzites and carbonates [e.g., Milnes and Schmutz, 1978; Pfiffner et al., 1990]. At its base the Suretta nappe overlies Mesozoic carbonates of the Splügen zone, which represents a 10- to 500-m-thick slab that extends over a distance of more than 20 km. This Splügen zone can be subdivided into a lower part which represents the autochthonous cover of the Tambo basement and an upper part consisting of slices of allochthonous units [Blanc, 1965; Strohbach, 1965]. Considering the regional axial plunges [cf. Pfiffner et al., 1990], the reflections at 1 s beneath Sovrana extending to the north can readily be correlated with the Splügen zone. To the north the base of the Suretta nappe is known to steepen reaching the surface south of Zillis. The Suretta nappe contains Triassic carbonates (called "internal Trias" by Milnes and Schmutz [1978]) which form a more or less continuous band [Pfiffner et al., 1990] separating two basement units of the Suretta nappe as shown in interpretations A and B in Figure 4. This intercalation of basement and cover rocks is the probable source of the reflections at 1 s beneath Cröt.

The next unit down, the Tambo nappe, consists almost exclusively of basement rocks. It overlies the Misox zone, a thin slab of Mesozoic carbonates and schists which also contain lenses of basement rocks and ophiolitic material (prasinites). The Misox zone is expected to lie at about 3 s beneath Cröt. Further south it rises toward the surface to overlie the Chiavenna Ophiolites [Schmutz, 1976] 10 km south of Sovrana. The Chiavenna ophiolite body is likely to be triangular shaped in a cross section, but its shape is ill constrained by surface data. Therefore we present an interpretation A with this body completely pinched out, as opposed to interpretations B and C with a thick ophiolite body. As Schmutz [1976] was able to show, this ophiolite body is in an inverted position. Its northern continuation is likely to be found in the Misox zone, and thus it is possible that the Chiavenna ophiolite body overlies Mesozoic sediments, as indicated in the geologic cross section of Figure 6.

On the basis of surface geology the front of the Tambo basement nappe can be projected beneath Ausserferrera, where it would correlate with a north dipping group of reflections at 1-2 s beneath that locality (Figures 4, A, B, and C). The Misox zone widens to the north, being composed of a number of thrust sheets of cover rocks [Gansser, 1937; Nabholz, 1945]. The two topmost units, the Tomül and Grava nappes, comprise a thick monotonous sequence of argillaceous to sandy to calcareous sediments, which are called Bündnerschiefer [Nabholz, 1945; Jäckli, 1941, 1944]. They are intensively folded, which may in part explain the lack of reflections in the top 1 s north of Zillis. The underlying Aul nappe contains several slivers of ophiolite material (partly gabbroic prasinites and serpentinites) and larger bodies of calcareous marbles [Nabholz, 1945]. These rock assemblages are likely candidates for providing the numerous reflections observed at 1-1.5 s beneath Canova, Thusis, and Zillis. The Vals and Terri thrust sheets indicated in the geologic cross sec-

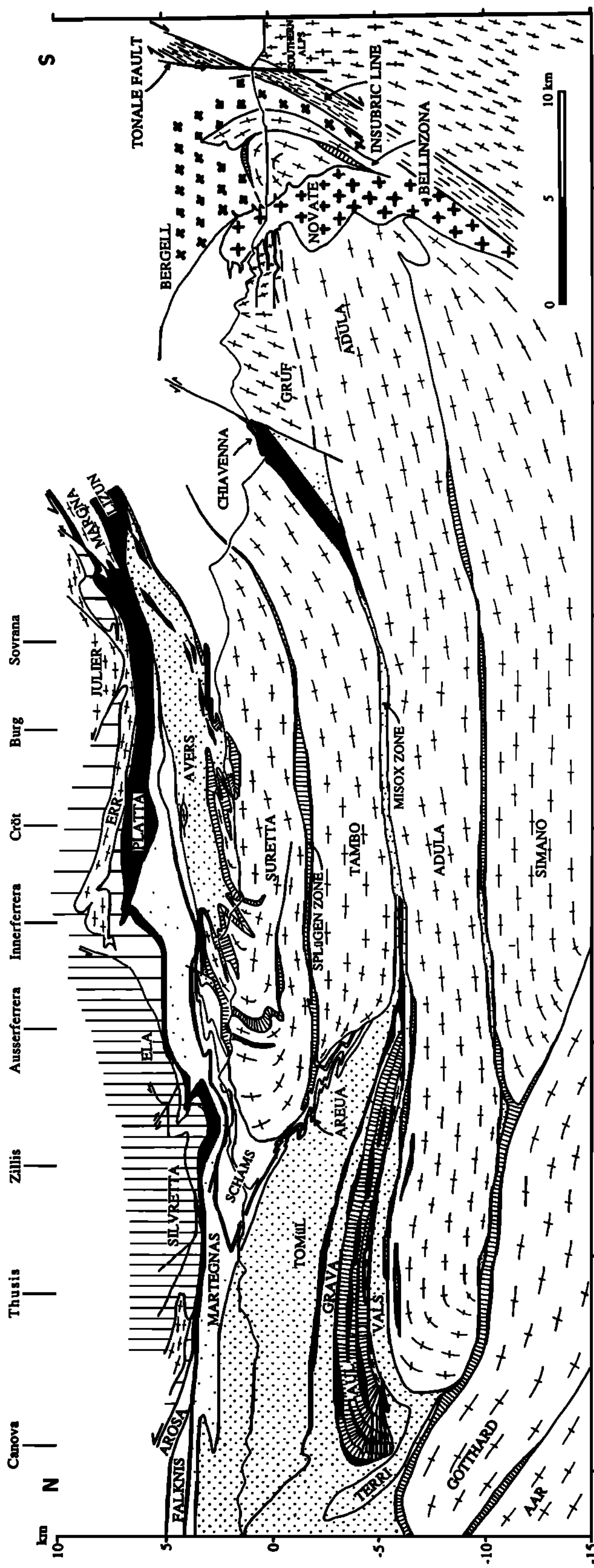


Fig. 6. Geologic cross section of the southern half of NFP 20-EAST based on the interpretation of the seismic data (Figure 4, Plates 2 and 4) and on regional structural style. The trace of the cross section is straight N-S following km 755 of the Swiss National Grid net (see Figure 2).

tion of Figure 6 consist of Bündnerschiefer as well [Kupferschmid, 1977; Probst, 1980] and are thus possibly less reflective.

The underlying Adula nappe consists of basement rocks topped by remnants of Triassic quartzites and carbonates. Projections of surface data [Pfiffner et al., 1990] 20 km (!) west of the seismic line place the top of the Adula nappe at around 2 s beneath Zillis and 3 s beneath Cröt. The reflections (H in Plate 4) observed at these places are interpreted as defining this boundary in models A, B, and C in Figure 4. To the south of the profile the Adula nappe steepens to form a south facing antiform [see Pfiffner et al., 1990, and references therein] shown in the geologic cross section of Figure 6. The northerly dip of the reflection group at 2.7 s beneath Sovrana (I in Plate 4) is an indication of this steepening. Northward the situation is less clear. The Adula nappe has a steep frontal zone, similar to the Tambo and Suretta nappes (see Figure 6 and Löw [1987]. But the Adula frontal zone does not have a constant trend and axial projection can thus only place it somewhere between shot points Thusis and Canova. Interpretations A and B place the Adula frontal zone in a northern position, whereas C shows it in an even more southerly position. However, both interpretations relate the front of the nappe to north dipping reflections, as expected from its observed map shape. The expected diffraction patterns from the steep nappe fronts such as the Adula and Tambo were not identified on the seismic sections. This may be a result of spatial interference from the complex structures which strengthens only the subhorizontal phases [Hurich and Smithson, 1987].

According to our interpretation there are a number of reflections within the interior of the Adula nappe. These might arise from strongly foliated paragneisses, contacts between paragneisses and tabular shaped Late-Variscan orthogneisses, and/or thin slabs of Mesozoic (?) carbonates contained within the Adula basement. All of these contacts and the foliation are subparallel to the top of the Adula nappe [see Pfiffner et al., 1990, and references therein], similar to the reflection pattern, but we refrain from identifying any particular reflection in view of the uncertainties and the considerable projection distance.

The contact between the Adula nappe and the underlying Simano nappe is characterized by a thin zone of Mesozoic amphibolite grade carbonates and schists that thin southward, making the identification of the two nappes very difficult. Projection of surface data [Pfiffner et al., 1990] places the top of the Simano nappe between 4 and 5 s beneath Ausserferrera-Sovrana as indicated in interpretation A and B in Figure 4. The Simano nappe is taken to encompass the underlying Leventina granite-gneiss, from which it is separated by small lenses of carbonates in the extreme south and north. To the north the Simano nappe is separated from the Lucomagno basement by the tight Molare Syncline, and the Lucomagno basement is in turn separated from the Gotthard massif basement by the tight Piora Syncline. Following Milnes [1974], the Gotthard, Lucomagno, and Simano-Leventina basement blocks can be viewed as a single basement complex, the "Subpennine complex." The structural relationships between these basement blocks (Piora and Molare synclines, for instance) are observed in outcrop almost 50 km west of the seismic line. It is doubtful that these structures can be projected as far east as the seismic profile, and if so, cylindrical projection has certainly approached its limit (see Pfiffner [1978] for an evaluation of the lateral continuity of folds and thrust sheets in the adjoining Helvetic zone).

The discussion of lateral continuity applies equally well for the Gotthard massif and the Tavetsch massif. The relevant question for the interpretation of the seismic data is whether or not a subsurface extension of these basement massifs is to be expected in the seismic profile. The Tavetsch massif is a 5-km-thick sliver of basement rocks situated between the Aar massif and the Gotthard massif. It thins out to the east and represents the substratum of the Axen nappe proper of the Helvetic nappes [see Trümpy, 1969]. Both units are observed at outcrop 30 km east of the seismic profile. At its eastern end the Tavetsch massif cores an anticlinal structure in the Permian Verrucano. Its fold axis changes from a WSW-ENE trend to a WNW-ESE trend going east. In addition, the basal detachment of the Helvetic nappes steps up from the basement into the Mesozoic cover going east. It is probably situated in shaly sequences of the Jurassic along the seismic profile. All these points suggest that the Tavetsch massif is unlikely to be expected in the seismic profile and does therefore not appear on our interpretation (Figure 4).

The Gotthard massif, on the other hand, probably represents the substratum of the higher Säntis-Drusberg nappe [Pfiffner, 1985; Wyss, 1986] and is more likely to be encountered in the NFP 20-EAST transect. The three varying interpretations A, B, and C presented for the Gotthard massif illustrate the degree of uncertainty. In A the line of reflections (D in Plate 4) extending from 1.5 s beneath Rothenbrunnen to 5.5 s beneath Ausserferrera, which is also evident in the explosion seismology data [Pfiffner et al., 1988], is interpreted to represent the interface between Bündnerschiefer and underlying basement. In the north this boundary is the top of the Aar massif, which, according to extrapolation of surface data [Pfiffner et al., 1990], is expected at a depth of 1-1.5 s just north of Rothenbrunnen. Further south the line of reflections outlines the envelope of basement tops, but the existence of seismically transparent subvertical contact zones between basement slabs such as observed in outcrop west of the seismic line is not ruled out. This interpretation resembles the one adopted in the Western Alps by Bayer et al. [1987] and Tardy et al. [1990], who denote the equivalent contact with "frontal Penninic thrust." The north dipping reflections at around 5 s beneath Zillis are interpreted as part of a bow tie structure produced in the region of the north dipping top of Simano nappe and the basal Penninic thrust.

In model B of Figure 4 the top of the Aar massif is taken to dip steeply south, similar to the Urseren zone farther west [cf. Pfiffner et al., 1990]. The assumed shape of the Gotthard massif corresponds roughly to that observed in the Lukmanier area (compare, for example, Probst [1980]). Its steeply dipping southern flank is due to a late phase of "backfolding" in the western part of the Gotthard massif [Pfiffner et al., 1990, and references therein] and to synsedimentary Early Jurassic faulting in the eastern part [Etter, 1987]. The crossing of the reflections related to the top of the Gotthard massif and the Simano nappe beneath Zillis would again represent a bow tie structure.

In interpretation C, Aar and Gotthard massifs are separated by a steep, seismically invisible suture comparable to the Urseren zone discussed for interpretations A and B. The north dipping reflections near 5 s beneath Zillis are interpreted in terms of "backthrusting", i.e., a north dipping thrust with movement "top to the south" associated with the late phase of "backfolding" affecting the suture between the Helvetic and Penninic zone ("Northern Steep belt" of Milnes [1974]). This interpretation is also used to explain north dipping reflections beneath the Penninic nappes in Western Switzerland [DuBois et al., 1990a].

Deep Structures

As pointed out by Meissner [1989] and Chadwick et al. [1989], the origin of lower crustal reflections is subject of considerable debate; they have been attributed to shear zones, igneous, metamorphic, and lithological layering of varying types, or the presence of fluids or anisotropies in these rocks. Chadwick et al. [1989] and Meissner [1989] conclude that orogenic terrains are characterized by a strongly reflective lower crust but that this correlation does not necessarily hold for extensional terrains. Lower crustal reflectors were never drilled, but insight can be gained from comparison with exhumed lower crustal sections, such as the Ivrea zone in the Alps. In doing so it must be kept in mind that unlike the European crust of the northern portion of the NFP 20-EAST profile the crustal material of the Ivrea zone suffered considerable Mesozoic extension [Handy, 1987] prior to collision.

The reflection band (M in Plate 6) at 11-12 s observed at the northern end and extending southward to greater depths (14.5-15.5 s beneath Canova) corresponds to the Moho as defined by refraction [Müller et al., 1980] and explosion seismology studies [Pfiffner et al., 1988]. Converting the refraction data to a time section places the crust-mantle boundary at around 12.5 s at the northern end of the section and at around 16 s beneath Canova (see Figure 7), i.e., the refraction Moho corresponds more closely to the bottom limit of the reflection band seen in the reflection experiment. As pointed out by Pfiffner et al. [1988], this reflection band might represent a transition zone from lower crustal to upper mantle velocities which would be beyond the resolution

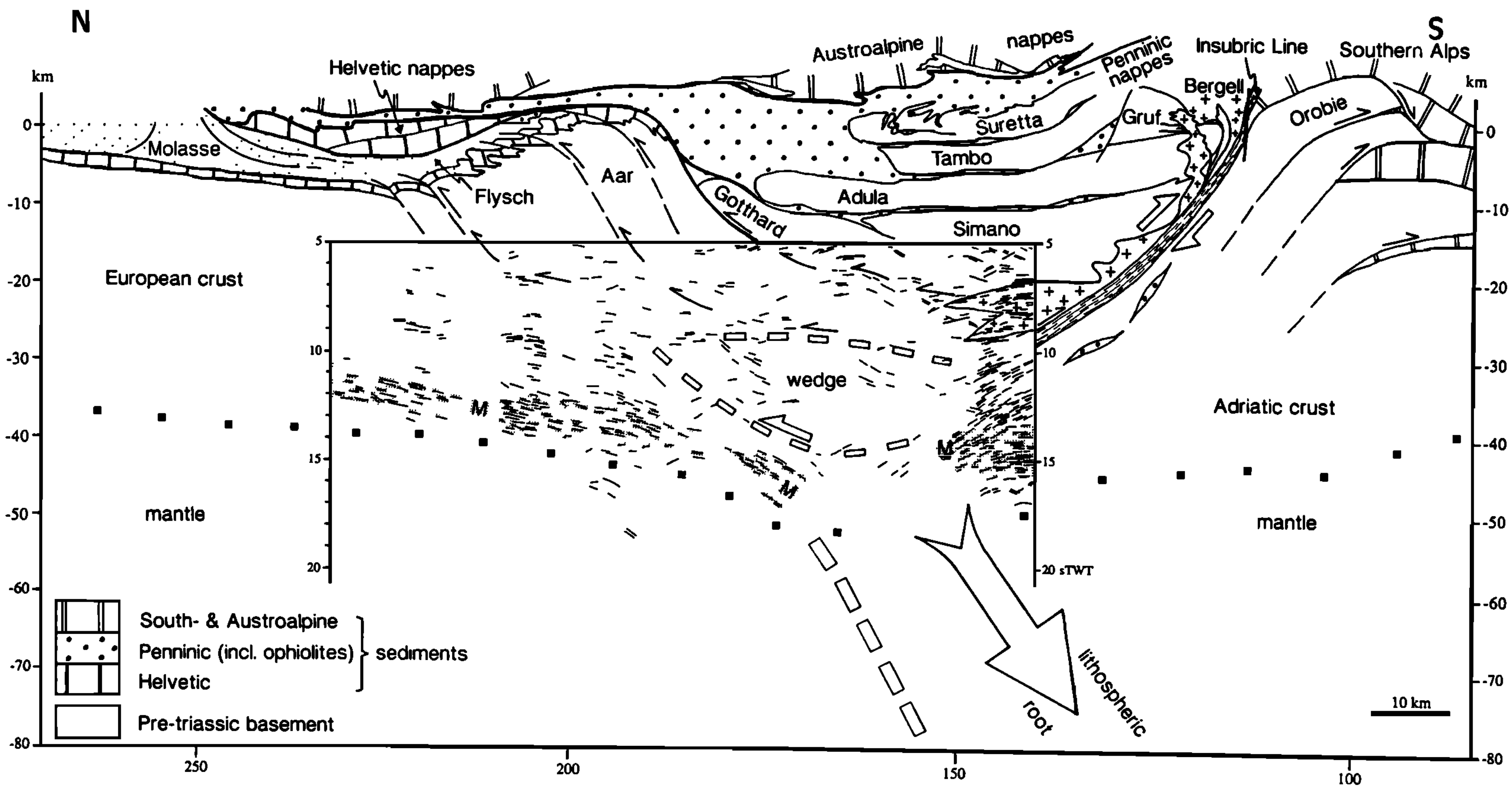


Fig. 7. General geologic cross section based on the interpretation of the seismic data. The line drawing in the deeper part of the crust is based on the seismic data of Plate 6. The section extends beyond the seismic line NFP 20-EAST to the north and south and follows km 755 of the Swiss National Grid net. Stippled (M) areas indicate reflection Moho, solid squares indicate refraction Moho.

of refraction seismology. In contrast to the explosion seismology data, in which Moho reflections abruptly ended beneath Canova, in the Vibroseis data, Moho reflections are apparent as far south as Thusis, where they disappear at 15-16 s with a relatively steep southerly dip. At the southern end of the section, Moho reflections at 14-15 s are tentatively interpreted as originating from the crust-mantle boundary of the Southern Alps. The important feature is the Moho gap between Thusis and Cröt, which is located near where crustal subduction may have severely disturbed the crust-mantle boundary during Alpine orogeny.

The sparse, discontinuous reflections at around 8-9 s TWT in the northern part of the section (L in Plate 6) occur within a seismic refraction determined low-velocity zone [cf. Müller et al., 1980] that has been interpreted as a granitic layer. An origin of these reflections due to the presence of fluids released in devolatilization reactions was evoked by Pfiffner et al. [1988]. Some of these events are shorter than the diameter of the first Fresnel zone (limit of horizontal resolution) and may thus be due to diffractions from lateral inhomogeneities caused by irregularly shaped rockbodies rather than from horizontal layering.

The transparent lower crust typical of almost the entire length of the NFP 20-EAST profile differs from the strongly reflective lower crust found beneath the Variscan and Caledonian orogens in Europe [c.f. Bois et al., 1988; Chadwick et al., 1989; Lüschen et al., 1987]. There are a number of reflections near the southern end of line NFP 20-EAST (see Plate 5) between 5 and 8 s, including a very coherent reflection at 6.7 s, which correspond to structures deeper than the lowermost units exposed in the Alps. Their identification therefore remains highly speculative. One possible explanation would be that some of these reflections are generated from granitoid rocks related to the late- to post-tectonic composite Bergell Intrusion, which crosscuts the nappe boundaries. This intrusion is in part tabular shaped (e.g., the Bergell Granodiorite), and swarms of dykes related to the Novate Granite are known to extend north over several kilometers.

Some of the prominent north dipping reflections situated between 8 and 13 s at the southern end of the line (N1-N2 in Plate 6) are tentatively correlated to an important crustal-scale shear zone, the Insubric Line. This north dipping mylonite belt separates high grade rocks of the Penninic zone from the Southern Alps, which experienced little or no Alpine metamorphism. Extrapolation of surface data from the Insubric Line to the north places the Insubric Line at about 8 s TWT beneath shot point Sovrana. Considering this geometry and the effects of migration, only the upper of these north dipping reflections can be correlated with the fault zone. The middle and lower zones of reflections seemingly originate within the lower crust of the Southern Alps, a point which will be discussed in more detail below.

SOME IMPLICATIONS CONCERNING CRUSTAL SCALE SHORTENING

Although the seismic line NFP 20-EAST, which crosses almost the entire Alps, has considerably added to the knowledge of the deep structure of the Alps, additional insight will be gained from the companion seismic lines through the Alps of western and southern Switzerland. Thus, rather than trying to discuss the Alps as whole, the following discussion will focus on implications for which NFP 20-EAST is particularly relevant. The geologic cross section in Figure 7 is an attempt to summarize these points.

Aar Massif and North-Alpine Foredeep

The Tertiary sedimentary infill of the North-Alpine Foredeep has been significantly shortened in its southern part, the Sub-Alpine Molasse. The resulting imbricate structure displayed at the surface displaces sediments of early Oligocene age (Lower Marine Molasse, UMM) and younger. Detachment occurred within shaly sequences of the UMM and shortening in the underlying substratum (Mesozoic sediments and pre-Triassic basement) must therefore be sought farther south. As discussed by Pfiffner [1986], there are two possibilities: (1) the basal thrust faults of the Sub-Alpine Molasse may rejoin the basal thrust of the Helvetic nappes or (2) they may link up with structures on the northern flank of the Aar massif. In solution 1 shortening within the basement would have been taken up by relative movement between the Gotthard and Aar massifs. In solution 2, shortening within the basement would be related to the formation of the Aar massif basement uplift. Although solution 1 may apply to the most internal thrust sheets of the Sub-Alpine Molasse, solution 2 seems more plausible [cf. Pfiffner, 1986] considering constraints from metamorphism, thrust displacements, and the regional geology. In the cross section of Figure 5 this basement shortening is accomodated by a set of structures representing a combination of folding and faulting. The magnitude of the basement uplift from about 7 km below to 1 km above sea level requires a crustal-scale balance. Although the seismic line does not yield much data on the nature of structures associated with this shortening at depth, the depression of the Moho suggests that this shortening produced a thickened upper and lower crust. It has to be noted that the amount of basement uplift becomes even more important in central Switzerland [see Pfiffner et al., 1990, Figure 1]; here shortening of the Mesozoic cover in the Jura Mountains may also be accommodated by the Aar massif basement uplift.

Bedlengths of Mesozoic strata shortened by about 10 km to an actual length of 47 km, as measured between a point situated at the southern end of the undisturbed Plateau Molasse in the north and a point on the southern flank of the Aar massif in the south. This shortening is responsible for the bulge of the Aar massif and is probably also responsible for the increase in crustal thickness from 35 km measured beneath the Plateau Molasse to 45 km beneath the Aar massif on its southern flank. Comparing the area of structural relief defined by the Aar massif bulge to the curvimetric shortening of the Mesozoic strata suggests a detachment of the Aar massif at some 14 km below the basement top. This detachment level was used to constrain the upper limit of the crustal wedge of the Adriatic Plate in Figure 7.

Crustal Subduction Beneath the Penninic Zone

Inspection of the Penninic zone shown in the summary Figure 7 reveals that the upper crustal basement nappes form a four (or more) fold stack and thus require a substantial volume of lower crust for reasons of volumetric balancing. This volume is apparently not available in this cross section. Instead, one is forced to conclude that lower crustal material has been subducted, and the most obvious place where this may have occurred is the Moho gap identified on the Vibroseis data. Subduction of lower crust has already been postulated by Laubscher and Bernoulli [1982] and Trümpy [1988]. An accurate mass balance is, however, rendered difficult for the following reasons:

1. Unlike the Helvetic zone, where nappe transport was directed approximately south to north [Pfiffner, 1981, 1985], in the Penninic zone transport directions were less regular and include E-W components [see Pfiffner et al., 1990, and references therein], i.e., in and out of the section plane.

2. The thickness of the crust prior to Alpine orogeny is not yet well constrained, but it is likely that the crust had been thinned during Mesozoic rifting associated with Tethys formation.

3. The Moho may not behave purely as a passive interface but rather may undergo postorogenic "ordering-processes" [Trappe et al., 1988]. This point is particularly important for those parts of the Alps which underwent the Cretaceous to Eocene orogenic phases (Penninic, Austroalpine, and South-Alpine domains). It is possibly less relevant for the European crust of the Helvetic zone which was mainly deformed in Oligocene-Miocene times.

4. An accurate material balance should incorporate effects associated with the complex metamorphic history of the rocks involved (e.g., high-pressure metamorphism in the Adula nappe) and effects of the subduction suture that is truncated by the Insubric Line near the Bergell Intrusion but which must have a continuation at depth.

An expression of subduction can be found in the lithospheric root situated just south of the seismic line (Figure 7) beneath the Southern Alps. This root, which is the result of subduction, consists of rocks with seismic velocities typical for lithospheric mantle and extends down to a depth of some 200 km [Müller and Panza, 1986]. The crustal root reaches down to 55 km in this region based on refraction measurements [Müller et al., 1980].

In a general way, Figure 7 illustrates the late-stage continent-continent collision, where upper crustal material escaped upward and in both northward (Aar and Gotthard massifs) and southward directions (Southern Alps and Insubric Line), similar to a "pop-up" structure. Movements associated with this detachment of upper crustal rocks seemingly occurred in an intricate succession. They were Late Cretaceous to middle Eocene and late Oligocene to late Miocene in the Southern Alps [Brack, 1981; Doglioni and Bosellini, 1987], and late Oligocene and Miocene along the Insubric Line [Hurford, 1986; Heitzmann, 1987]. In the north, Oligocene movements for the Gotthard followed by Miocene movements for the Aar massif best explain the evolution of the North-Alpine Molasse Basin and the deformational history of its hinterland [Pfiffner, 1986].

The depression of the Moho, combined with detachment and uplift of upper crustal rocks, could also be related to a lower crustal delamination and indentation. Hereby a wedge of lower crust of the Southern Alps (Adriatic Plate) is thought of as forced into the lower crust beneath the Aar massif (European Plate), splitting it apart and thickening the crustal section. In Figure 7 the delamination is interpreted as occurring along the detachment level between upper and lower crust in the Aar massif and the deeper parts of the Penninic zone. The putative wedge probably underwent severe internal deformation which may have altered its original reflective seismic character.

The Southern Alps

In the Southern Alps, basement slabs were raised by "top to the south" movements to a height 5-10 km above the autochthonous basement-cover contact beneath the northern margin of the Po Plain. An example is the basement slab of the Orobie in Figure 7, which in its uppermost part was drawn after Laubscher [1985]. Shortening in this section is of the order of 40 km according to Laubscher [1985], which suggests that the basal thrust faults of the basement slabs are likely to reach deep into the crust as indicated in Figure 7. They might be associated with more ductile shear zones with significant velocity anisotropy at greater depth, similar to the contacts between the basement nappes in the Penninic zone, and might therefore be responsible for some of the deeper north dipping reflections beneath Sovrana in the seismic section. Additional reflections might be due to lithological banding in the suture zone between the Penninic and Austro-South-Alpine zones. Finally, lower crustal reflections in the Southern Alps may also be caused by shear zones associated with Mesozoic crustal stretching. As discussed by Handy [1987], Jurassic crustal stretching indicated by the sedimentary record is related to the formation of the Pogallo ductile fault zone which produced a crustal thinning of about 5 km.

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