TECTONICS, VOL. 12, NO. 4, PAGES 925-935, AUGUST 1993

CRUSTAL STRUCTURE AND REFLECTIVITY OF THE SWISS ALPS FROM THREE-DIMENSIONAL SEISMIC MODELING: 2. PENNINIC NAPPES

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Abstract. Surface geological mapping, laboratory measurements of rock properties, and seismic reflection data are integrated through three-dimensional seismic modeling to determine the likely cause of upper crustal reflections and to elucidate the deep structure of the Penninic Alps in eastern Switzerland. Results indicate that the principal upper crustal reflections recorded on the south end of Swiss seismic line NFP20-EAST can be explained by the subsurface geometry of stacked basement nappes. In addition, modeling results provide improvements to structural maps based solely on surface trends and suggest the presence of previously unrecognized rock units in the subsurface. Construction of the initial model is based upon extrapolation of plunging surface structures; velocities and densities are established by laboratory measurements of corresponding rock units. Iterative modification produces a best fit model that refines the definition of the subsurface geometry of major structures. We conclude that most reflections from the upper 20 km can be ascribed to the presence of sedimentary cover rocks (especially carbonates) and ophiolites juxtaposed against crystalline basement nappes. Thus, in this area, reflections appear to be principally due to first-order lithologic contrasts. This study also demonstrates not only the importance of three-dimensional effects (sideswipe) in interpreting seismic data, but also that these effects can be considered quantitatively through three-dimensional modeling.

INTRODUCTION

The success of deep seismic reflection profiling in revealing crustal structure has now established this method as a standard tool for crustal studies [e.g., Hauser and Oliver, 1987]. However, the goal of recovering deep crustal geology from seismic reflections is often elusive since, unlike conventional seismic data, direct ties to geology (e.g., wells) are generally lacking. Here we take advantage of a combination of unusually good seismic, geologic, and physical properties data in order to link reflections with specific geologic features by producing a model of the upper crust in the Penninic Alps.

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Paper number 93TC00363.
0278-7407/93/93TC-00363$10.00

Discerning the nature and geometry of crustal reflectors is an important step toward fostering the understanding of crustal structure and ultimately deciphering the complex tectonic history of this classic collisional orogen. Moreover, these results may contribute clues to the origin of similar crustal reflections in areas where geologic control is more limited.

Geologic Setting

In eastern Switzerland, the Penninic zone is bounded by the basal Penninic thrust, which separates it from the underlying parautochthonous basement massifs of the Helvetic zone to the north (Figure 1), and (south of the study area) the Insubric Line, south of which lie the Apulian rocks of the Southern Alps. The Penninic nappes formed when intense deformation during Alpine compression caused several slices of the upper crust of the European continental margin to be thrust tens of kilometers toward the European continent, with accompanying folding. The resulting stack of basement nappes is up to 15 km thick; at least an equivalent thickness has probably been eroded. The basement nappes were stripped of most of their clastic sedimentary cover early in the collision stage. These cover rocks now form, among others, the Bündnerschiefer and Schams nappes. However, many of the oldest (mostly Triassic) units, principally carbonates, remained attached to their crystalline substratum (though they may have been deformed or tectonically attenuated). Subsequent to nappe formation, structure has been repeatedly modified by a series of events, most notably a late stage of backfolding in the south (see Trümpy [1980], Pfiffner et al. [1990*a*], Schmid et al. [1990] for reviews of Penninic tectonics).

Particularly good exposures and relatively steep dips combined with extensive field mapping in the rugged terrain have revealed the shallow three-dimensional structure of the Suretta, Tambo, and Adula nappes [Milnes and Pfiffner, 1980, Pfiffner et al., 1990*a*]. These slices of gneissic Variscan basement, each up to several kilometers thick, are separated by generally thin zones of Mesozoic sedimentary cover [Milnes and Schmutz, 1978]. They have each been thrust tens of kilometers to the NNW and now constitute east plunging basement slabs with north facing frontal antiformal closures. The eastern plunge provides an opportunity to peer deep into the roots of the mountain belt through extrapolation via downplunge projection; however, lack of subsurface data has heretofore made extension to depth largely speculative.

Seismic Data

The Swiss seismic reflection profile NFP20-EAST, collected in 1986 as the first in a series of traverses, extends some 120 km across eastern Switzerland (Figure 1). The southern end of this profile crosses into the Penninic zone where the Adula, Tambo, and Suretta nappes should be present in the subsurface. Low-fold explosion data [Pfiffner et al., 1988] augmented the Vibroseis CMP reflection profile [Pfiffner et al. 1990*b*]. Processing of the Vibroseis data was conducted by Eidgenössische Technische Hochschule (ETH), Zurich [Valasek et al., 1990] and GRANSIR, Lausanne [duBois et al., 1990].

Notable among the Vibroseis results is the observation of numerous strong reflections in the upper crust of the Penninic zone. Pfiffner et al. [1990*b*] ascribe many of these reflections to nappe surfaces. In this study, we attempt to verify this hypothesis quantitatively and to map the deep structure of these features seismically, using three-dimensional modeling to link reflections to geologic structures seen in the field.

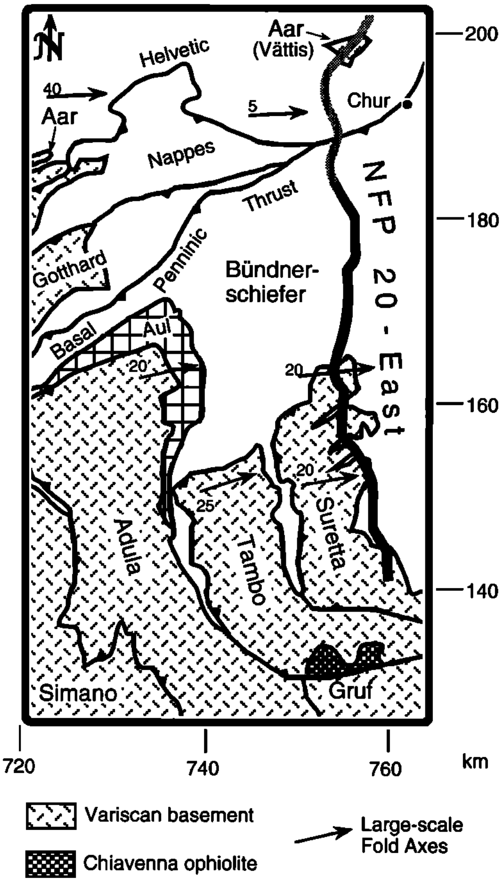

Fig. 1. Generalized geologic map of the Penninic zone of eastern Switzerland showing location of basement nappes and seismic line NFP20-EAST; bold portion of line is used in this study. See Stäuble et al. [this issue] for general location.

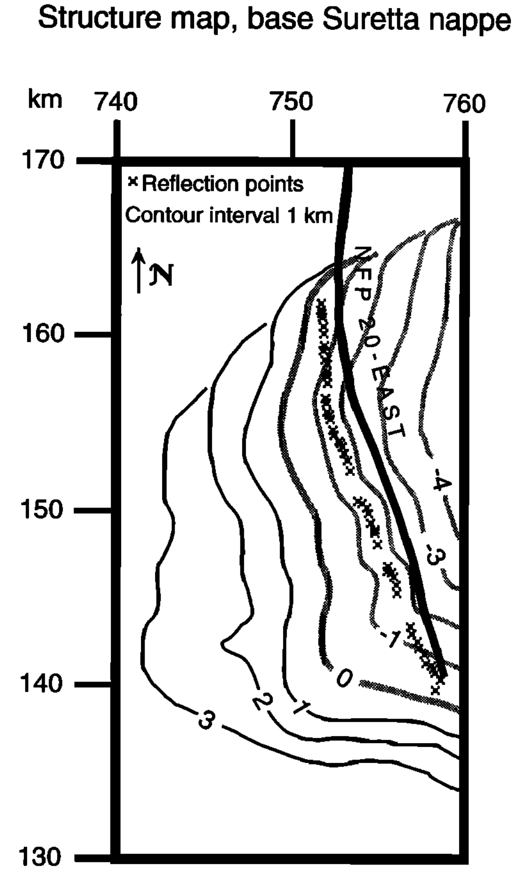

Fig. 2. Structure contours of the base of the Suretta nappe. Solid contours are based on surface mapping [Pfiffner et al., 1990a]; shaded contours are extrapolated based on seismic results (this study). Synthetic reflection points (crosses) depict the eastern limit of subsurface control. Southern portion of seismic line midpoints is shown by heavy line. Coordinates are in Swiss national grid and altitude system.

Following encouraging initial results [Litak et al., 1988], Stäuble et al. [1993, this issue] have applied a similar technique to investigate the seismic response of the Helvetic Zone farther north. Taken together, these two studies compose a comprehensive model of the upper crust for most of the 120 km length of the seismic profile.

METHOD

The first objective is to explain the origin of the principal reflections observed on the southern portion of line NFP 20-EAST. Since nappe surfaces that crop out nearby and plunge beneath the seismic line are associated with strong lithologic contrasts, they are obvious candidates to produce these reflections. Here we investigate the viability of this interpretation by determining if surface trends of the nappes can be extrapolated in a geologically reasonable way that also can account for the major reflection features. Modeling results are inherently nonunique and can be used only to verify if an interpretation is viable; in principle, an infinite number of models can be generated that fit the data equally well. By requiring the model to satisfy geologic and physical properties data, however, much of the intrinsic ambiguity can be reduced. Those constraints are present here to a degree that is rarely achieved elsewhere in deep crustal seismology.

In the high relief of the Penninic Alps, detailed field mapping of the dipping nappe surfaces has yielded contour maps of the near-surface structure for the Suretta, Tambo, Adula, and Simano nappes [Pfiffner et al., 1990*a*]. We have used the trends revealed by this mapping as the basis for a three-dimensional geometrical model of the stacked nappes beneath line NFP 20-EAST. Contours were extrapolated downplunge to determine if synthetic reflections from the nappes might have a gross geometry similar to that of the observed reflections (Figure 2). Whereas preliminary results were encouraging, the process was iterated to produce a best fit synthetic seismogram and a model consistent with known geology. The final model has dimensions of 60 km (north-south) by 20 km (east-west) and a maximum depth of 20 km.

For the Suretta nappe (structurally the highest), this process involved extrapolation of up to 14 km in distance and 5 km in depth to complete the entire model. However, extrapolation to the location of reflection points (the downdip limit of seismic control), is somewhat less, 9 km in distance and 3 km in depth (Figure 2). The deeper nappes involved extrapolation over greater distances (up to 25 km laterally and 16 km in depth for the top of the Simano nappe); their position is therefore less well constrained by surface data alone.

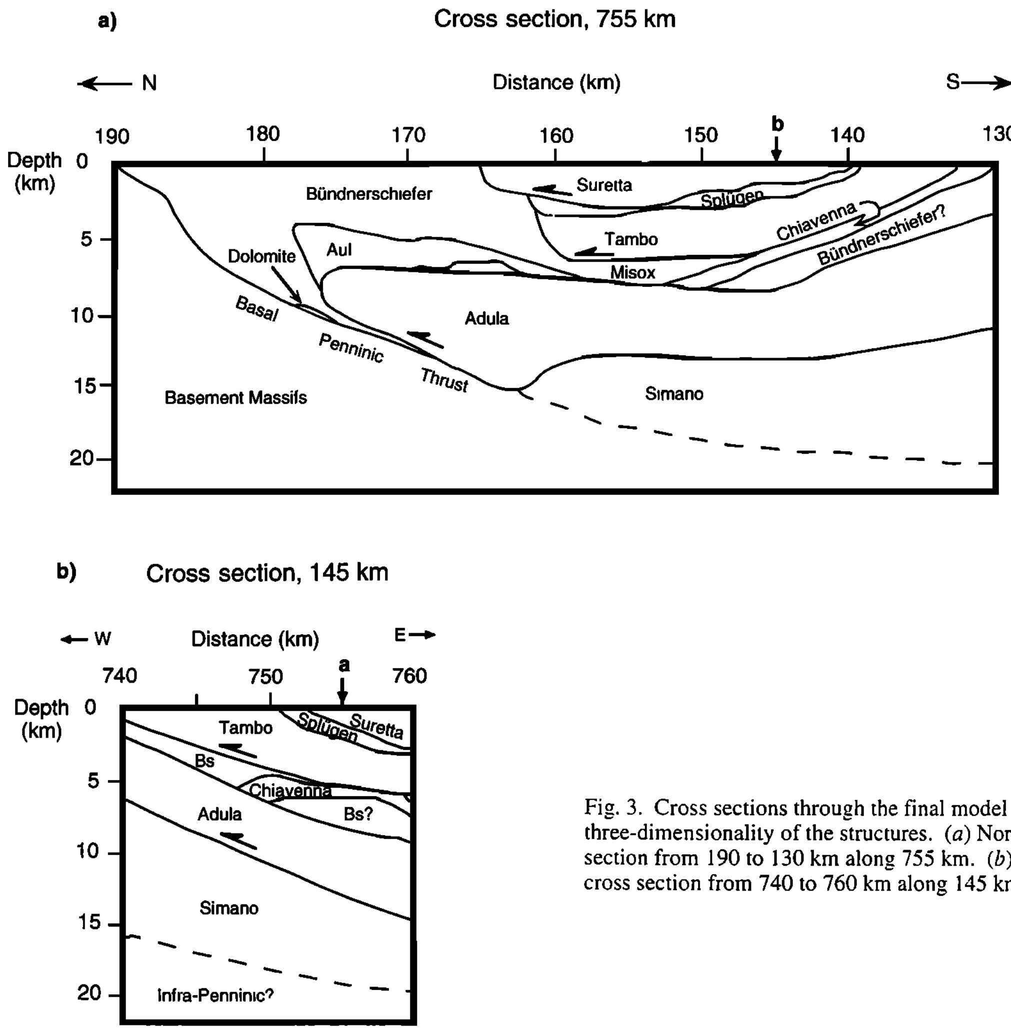

Fig. 3. Cross sections through the final model illustrating three-dimensionality of the structures. (*a*) North-south cross section from 190 to 130 km along 755 km. (*b*) East-west cross section from 740 to 760 km along 145 km.

Layers corresponding to the Chiavenna ophiolite, Bündnerschiefer (micaceous schists, sandstones, and shales), Aul nappe (mostly carbonates and ophiolite slivers), and carbonates overlying basement in the Lukmanier region, are also incorporated into the final model. Although no contour maps were available for these units, we extrapolated from outcrops to the south, west, and north (Figure 1) as depicted on the 1:500,000 scale tectonic map of Switzerland [Spicher, 1980]. Knowledge of their lithologies and structural relationships to the other nappes [Pfiffner et al., 1990*a*] helped to arrive at a solution compatible with the seismic data. The deepest layer corresponds to the top of the Aar and associated basement massifs. The Aar massif is exposed along the line at the Vättis inlier (Figure 1); contours based on a compilation by Pfiffner et al. [1990*a*] have been extended some 50 km to the south and east. Over much of the study area, this layer also corresponds to the basal Penninic thrust, which demarcates the Penninic realm from the more external Helvetic domain.

Layers corresponding to the base of Suretta, top and base of Tambo, top of Chiavenna and Aul, top of Bündnerschiefer, top and base of Adula, top of Simano, top of "Lukmanier" carbonates, and top of Aar were each digitized for gridding by Sierra Geophysics three-dimensional modeling software (Figures 2 and 3, as well as Plate 1, depict the final model). These layers delineate the major rock units in the area. We did not attempt to incorporate layering internal to these units, which is sometimes quite complex, or other second-order lithologic or structural variations. In many cases, including these effects would require downdip projection over a distance substantially greater than the scale of the mapped features themselves and is not warranted by the available constraints. Excellent control on velocities and densities was available from laboratory analysis of rock samples [Sellami et al., 1990, Table 1]. The effects of anisotropy, which ranges from 3% to 14%, were not explicitly considered. However, in foliated rocks, velocities normal to the foliation were used since, in general, this direction closely approximates the direction of seismic wave propagation for normal incidence reflections. A linear velocity gradient was applied to shallower units, where velocity is strongly depth-dependent.

Normal incidence ray tracing (zero-offset approximation) using Sierra's implementation of the WKBJ method [Frazer and Phinney, 1980] was performed, incorporating surface source and receiver locations equivalent to the southernmost 50 km of the seismic profile. To ease computation, the synthetic trace spacing is 400 m versus 80 m for the real data; that is, each synthetic trace corresponds to five real traces.

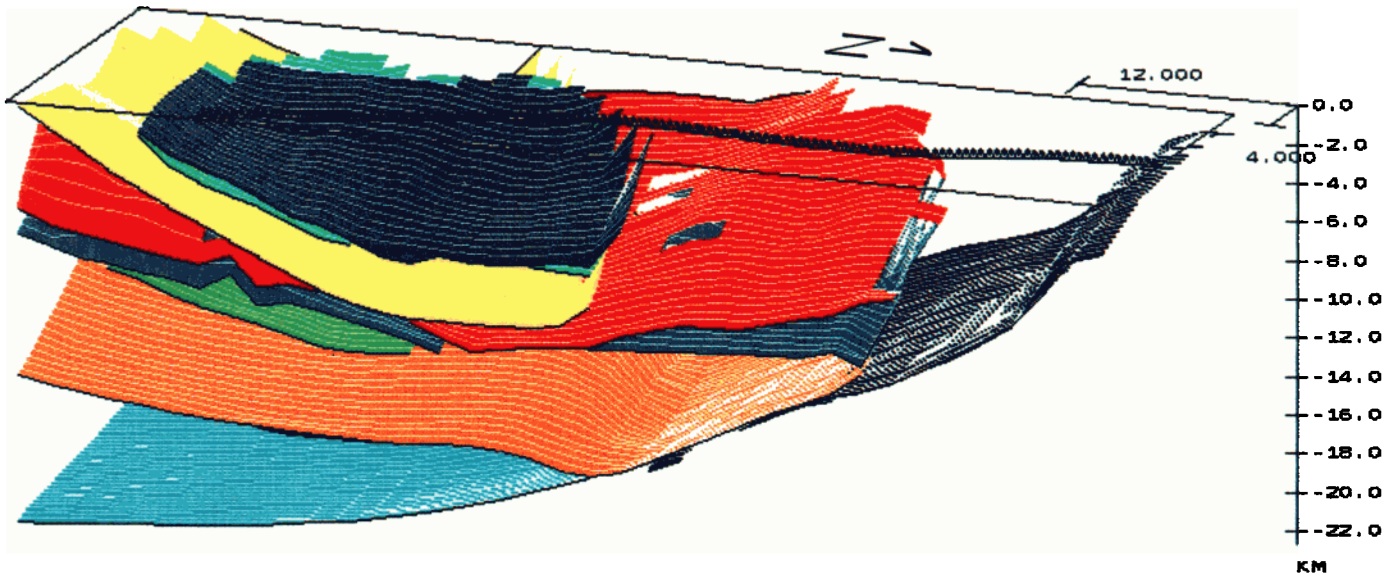

Plate 1. Three-dimensional perspective plot of final model viewed from east-northeast. Colors correspond to layers: dark blue, base of Suretta; blue-green, top of Tambo; yellow, base of Tambo; red, top of Aul and Chiavenna; blue, base of Aul and Chiavenna; green, top of Adula; orange, base of Adula; light blue, base of Simano; and purple, top of Aar massif. Black triangles indicate surface location of seismic line.

TABLE 1. Model Velocities and Densities

Unit	Velocity, km/s	Velocity Gradient, s^{-1}	Density, g/cc	Reference (Sample number)
Suretta	4.50	0.25	2.78	1 (pf9)
Splügen	5.94	0	2.69	1 (pf4)
Tambo	5.50	0.05	2.70	1 (pf7)
Bündner-schiefer	5.80	0.03	2.70	2
Chiavenna	6.75	0	2.95	2
Aul	6.75	0	2.70	1 (pf13)
Adula	5.83	0	2.64	1 (pf2)
Simano	5.95	0	2.70	1 (pf7)
Dolomite (Lukmanier)	6.90	0	2.83	1 (pf15)
Aar	6.35	0	2.62	1 (pf12)

Reference key: 1, [from Sellami et al., 1990]; 2, by analogy to similar rock types farther west [Sellami et al., 1993].

The resulting spike seismogram was convolved with a 10-45 Hz Klauder wavelet to mimic the acquisition and processing parameters used in the survey. A time-ramp gain was applied to correct for spherical divergence losses. Comparison to the real data suggested modifications to the model structure, and the process was iterated to produce an optimum match.

RESULTS

Plate 2 compares the resulting synthetic section to the actual data. A detailed comparison of reflection amplitude and geometry follows.

Suretta, Tambo, and Chiavenna

Strong, coherent north dipping reflections are recorded between 1 and 4 s at the south end of the line. The north dipping events from 1.1 to 1.7 s are modeled as reflections from the base of the Suretta (dark blue reflection in Plate 2) and top of the Tambo (green) nappes; the zone between these is the Tambo cover, known as the Splügen carbonates. Field relationships indicate that this zone thickens to the north, a phenomenon exhibited on the synthetic section by the divergence of the dark blue and green reflections near CMP 2270, and on the real data by a corresponding thickening of the intervening reflective zone (Plates 2b and 2c). Laboratory measurements indicate that the Suretta/Splügen and Splügen/Tambo interfaces possess fairly high reflection coefficients (RCs) of 0.06 and 0.04, respectively [Sellami et al., 1990], possibly enhanced by tuning effects in the south where the Splügen is thin. Variations in thickness of the Splügen can be followed north to approximately CMP 1900, where it again thickens and becomes mixed with the lower-velocity schists of the Bündnerschiefer. The base Suretta reflection continues to CMP 1870, where it abruptly steepens to crop out along the line. This part of the interface is not imaged seismically, perhaps either due to the steep dip, the lower impedance contrast with the Bündnerschiefer, or low fold of the data in the shallow section. The top of Tambo reflection is modeled as flattening out and terminating at CMP 1920. Again, the steeply dipping nose of the Tambo is not imaged on real or synthetic data.

The Chiavenna ophiolite body crops out some 10 km south of the seismic line (Figure 1), but its northern extent in the subsurface was previously unknown. We correlate a thin (~1 km) Chiavenna ophiolite with two strong north dipping reflections, about 300 ms apart, imaged between 1.9 and 2.4 s south of CMP 2230 (yellow and blue horizons in Plate 2a). This is an attractive option for several reasons. First, gravity modeling requires a relatively thin, high-density body in this location [Marchant et al., 1989]. Second, the high amplitudes of the reflections are consistent with a gneiss/ophiolite interface (RC = 0.08 in the model). Alternate interpretations, for example, a thin zone of Misox carbonates or internal reflections within the Tambo, fail to provide either the requisite density or impedance contrast. Furthermore, reconciling a deeper Tambo base with outcrops only 6 km south of the end of the line would require an unusually steep dip and sudden flattening of the Tambo base, a phenomenon not observed in outcrop. A complex of crossing reflections near CMP 2110 (shown in red in Plate 2a) manifests the transition from the north dipping Chiavenna reflections to the gently south dipping reflections from the underlying Adula nappe, and marks the termination of the Chiavenna ophiolite. This interference pattern of (unmigrated) crossing reflections closely approximates reflections observed on the real data (Plates 2b and 2c).

Moving farther north, the yellow reflection from CMP 2180 to 1920 now represents the weakly reflective Tambo base overlying metapelites of the Misox zone. The short reflective segment below CMP 1970 at 2.4 s (Plates 2b and 2c) may be due to varying lithology in the Misox, perhaps a carbonate lens. We interpret the change in reflection character near 2 s below CMP 1850 to denote the northward termination of the Tambo nappe. The south dipping reflections observed in the Vibroseis data within the Tambo (not modeled) may be due to layering of orthogneisses and paragneisses. The generally weak Tambo/Misox reflections indicate a small acoustic impedance contrast (RC ~0.02), consistent with gneiss overlying metapelites. For the same reason, the underlying Misox/Adula interface is also weakly reflective in this area (RC ~0.01), represented by the gently south dipping red segment from CMP 1940 to 2100 in Plate 2a. The low amplitudes of these reflections probably indicate that carbonates are not present in the Misox zone in this locality.

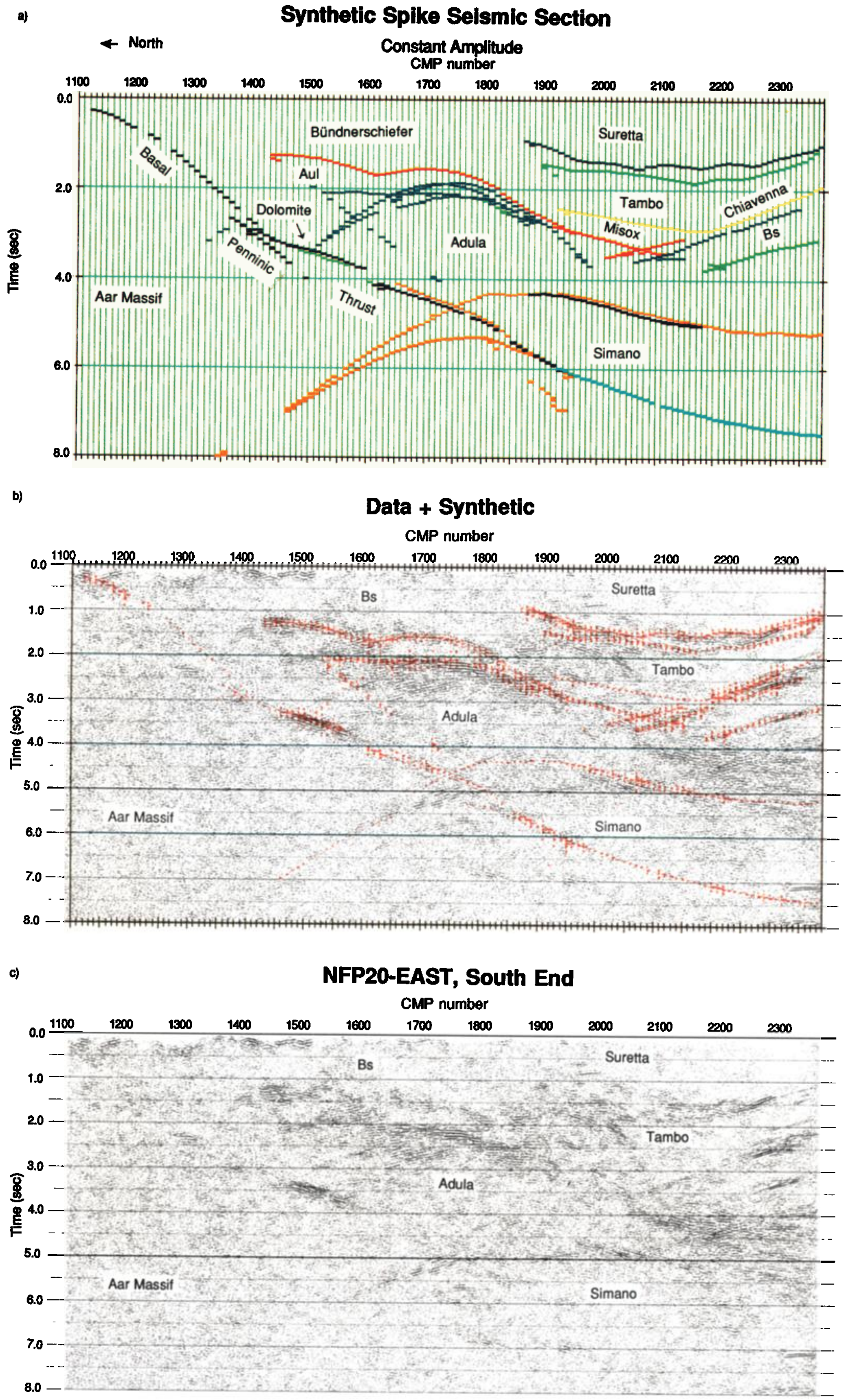

Plate 2 caption on page 931

Adula and Simano

Directly below the Chiavenna reflections, a single north dipping reflection below 3 s (green horizon in Plate 2) may be related to the top of the Adula basement nappe or a very thin zone of associated cover rocks, possibly Triassic carbonate. This much distance (~3 km) between the Tambo and Adula nappes is not observed in outcrop but derives naturally from downplunge projections of surface trends and seems required by the reflection geometry. The nature of the material above this contact is unclear. Two possible candidates are a wedge of Bündnerschiefer, although it is not known to be present in this area, or the Gruf gneiss, which crops out to the south (Figure 1) but is not thought to extend this far north. Since the velocities of these two units are similar and structural information indecisive, this study is unable to distinguish between these two possibilities. Because the Gruf unit is nowhere observed to extend north of the near-vertical (at the surface) Engadine Fault, it appears to be the less probable alternative.

The reflection character of the Adula top changes dramatically north of CMP 1940, from weak reflection fragments to a series of very strong, more laterally continuous reflections. This observation can be attributed to the presence of carbonates overlying Adula basement. The lowermost of these carbonates are remnants of Adula cover rocks, whereas the rest consist of a stack of nappes containing carbonates and interlayered metapelites and ophiolitic slivers. The uppermost strata form the Aul nappe, which represents a 1-km-thick sequence of carbonates with ophiolitic slivers. The onset of the Aul near CMP 1940 is indicated by the high-amplitude reflections at the basement/cover interface, stepping up from 2.4 s to the very strong reflections at 2.1 s on either side of CMP 1720, and continuing to the reflection at 2.0 s at CMP 1510 (blue in Plate 2a). The high amplitude of these reflections would be expected for a marble/gneiss interface, with a reflection coefficient of 0.09 [Sellami et al., 1990]. The multicyclic or layered appearance of these reflections and the observation of north dipping events from 2.2 to 3.0 s between CMPs 1610 and 1800 (Plate 2c), combined with the complex intercalations of carbonates, metapelites, and ophiolites seen in outcrop [Pfiffner et al., 1991], suggests that the north dipping events may be diffractions from sharp discontinuities associated with the Aul and related nappes. Although we have not attempted to model these reflections in detail, the inclusion of an irregular "bumpy" zone of Bündnerschiefer-type mica schists between the Aul and the Adula reproduces elements of both the layered reflections and the north dipping events (blue reflections in Plate 2a). Since these diffractive events emanate from multiple sources outside the plane of the seismic section, migration at any reasonable velocities is unlikely to collapse them fully.

The top of the Aul unit is evident as the discontinuous series of reflections between 1.2 and 2.0 s between CMP 1430 and 1850 (red in Plate 2a). Although the Bündnerschiefer/Aul contact nominally possesses a modeled reflection coefficient of 0.08, somewhat weaker reflections are observed than those at the base of the Aul, perhaps due to the gradational nature of the contact in the south. The short, discontinuous reflection segments at 1.2 to 1.5 s between CMP 1390 and 1550 may emanate from ophiolite slivers known to be associated with the Aul top or the sharper schist/carbonate contact in the north.

Proceeding deeper in the section and returning to the south end of the line, the discontinuous reflections from 4 to 5 s are not accounted for by any of the interfaces in the model. At present, it appears that these reflections originate from within the Adula nappe, possibly reflecting intensive isoclinal folding of orthogneiss and paragneiss layers (analogous to the intra-Tambo reflections), perhaps in conjunction with small carbonate lenses. They also may be related to the strong deformational fabric characterized by prominent foliation parallel to the top and bottom Adula basement contacts [Pfiffner et al., 1990*a*]. An alternate interpretation puts the Adula top deep enough to generate some of these reflections but requires a thick (~5 km) sequence of unknown material (possibly Bündnerschiefer and/or Gruf) above, and a steeply dipping, north striking Adula top.

South of CMP 1970, gently to moderately dipping reflections near 5 s coincide with the top of the model Simano nappe (orange horizon in Plate 2a). The strong reflection segment from 4.6 to 5.0 s between CMPs 2000 and 2150 (Plate 2c) probably indicates a thicker and/or more calcareous zone of cover rocks, represented by the purple horizon in the synthetic section (Plate 2a). Weak north dipping reflections below 4 s define an anticlinal structure with a crest near CMP 1900. Near CMP 1800, a very distinctive crossing pattern of reflections is observed from 4.5 to 5.5 s. Such a "bow-tie" pattern often indicates a buried-focus syncline; in the model, the termination of the Simano nappe against the basal Penninic thrust produces such a syncline. The resulting synthetic reflection pattern is strikingly similar to that observed, strongly bolstering our confidence in interpreting the Simano to terminate near CMP 1790.

Aar Massif and Basal Penninic Thrust

The deepest layer in the model corresponds to the top of the Aar Massif, which coincides with the basal Penninic thrust over much of the study area. Mapped in outcrop along the line, the Aar Massif dips shallowly southward and may be identified as the weak reflection above 0.5 s between CMP 1100 and 1200 (Plates 2b and 2c), corresponding to the purple horizon on the synthetic section (Plate 2a). Surface mapping suggests that somewhere near CMP 1200, dip may increase rapidly before decreasing again farther south. The steep segment is not well imaged and appears only as a weak diffraction tail on the synthetic section (Plate 2b). Somewhat farther south, however, a very strong dipping reflection between 3.2 and 4.0 s from CMP 1490 to 1620 has been interpreted as marking the interface between the Aar Massif and the basal Penninic thrust [Pfiffner et al., 1990*b*]. We interpret this strong reflection segment (green horizon in Plate 2a) as emanating from a carbonate pod analogous to those exposed upplunge in the Lukmanier region, near 730 and 175 km (Figure 1). A much fainter continuation of this reflection can arguably be traced down to CMP 1800 at 4.6 s. These

Plate 2. (*a*) Constant-amplitude synthetic spike seismic section showing reflection geometry. Colors correspond to Figure 3. (*b*) Spike section convolved with 10-45 Hz Klauder wavelet, amplitudes corrected for spherical divergence only (in red), overlain on southern end of seismic line NFP20-EAST, final unmigrated stack, adjacent traces summed. (*c*) Southern end of line NFP20-EAST. Each 100 CMPs corresponds to 4 km.

reflections are geometrically mimicked by the linear portion of the purple horizon on the synthetic section. While we ascribe these reflections to the Aar massif, it is also possible that some of them may be due to the overlying Gotthard massif, which crops out farther west. The eastward extent of the Gotthard is unknown; without clear reflection evidence for its presence, it is omitted from the model.

It is uncertain how or whether this reflection extends farther south, but a straightforward projection of this structure to depth links it to the moderately strong horizontal reflections at the south end of the line at 7.8 s. Although extending the contours of the Aar structure downdip allows a natural link to the deeper reflection (light blue horizon in Plate 2), such an extension remains highly speculative. However, the existence of such a midcrustal "detachment" separating the Penninic Zone from autochthonous European basement is consistent with the structure of the Suretta, Tambo, and Adula nappes. Recent data from line NFP20-SOUTH image reflectors beneath the Simano nappe, suggesting the presence of "infra-Penninic" nappes between the Penninic Zone and truly autochthonous basement [Heitzmann et al., 1991].

DISCUSSION

Effects of Iteration

Construction of a model by simple downplunge projection of surface structural trends is sufficient to approximate many observed reflections. However, modification and iteration of the modeling process are necessary to effect optimal agreement with the seismic data, and thus to present a more accurate picture of subsurface structure. This can be illustrated by comparing our best fit model to the initial model of the Suretta, Tambo, and Adula nappes (Figure 4a). The latter is a "blind" extrapolation of surface trends; that is, reflection geometry was not considered in constructing the model. The synthetic seismic section resulting from this initial effort is similar in many respects to the seismic data (Figure 4b), validating the general interpretation of Pfiffner et al. [1990*b*]. Nevertheless, several structural modifications improve the fit considerably and alter the structural interpretation somewhat. Even the shallowest layer, the base of the Suretta nappe (Figure 2a), requires some adjustment to match the reflection geometry: The southern limb must dip less steeply than expected and is up to 800 m shallower in this area, indicating that the Splügen zone thickens more rapidly at depth than anticipated. In contrast, the top of the underlying Tambo nappe is very similar in both the initial and final models, although local variations of up to 500 m occur. However, the Tambo base is consistently 0.5 to 1.5 km shallower than predicted, signifying that the thickness of the Tambo nappe is more nearly constant compared to the initial model. The Tambo also probably extends some 2 km farther north. The Adula nappe likewise continues farther north, about 3 km. Otherwise, its top is fairly similar to the original model, with a slightly different shape. In the best fit model,

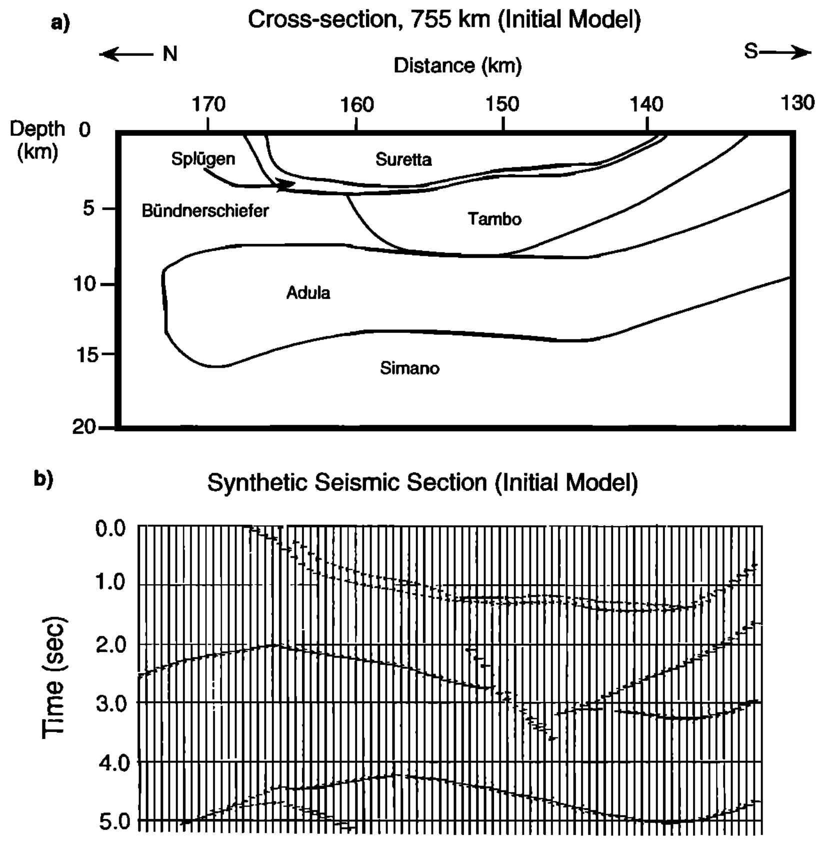

Fig. 4. (*a*) East-west cross-section of initial model along 755 km. This model was constructed solely by "blind" extrapolation of surface trends of the Suretta, Splügen, Bündnerschiefer, Tambo, and Adula units. Compare to final cross section in Figure 3a. (*b*) Corresponding synthetic seismic section, showing general similarity to Plate 2 but differing in some respects.

this surface is up to 500 m deeper in the north and 300 m shallower in the south, leading to a more exaggerated east-northeast trending syncline. The Adula base trends more southerly rather than southeasterly in the southern part of the study area, with a maximum difference in depth of 1.5 km. Another variation of about 1.7 km indicates a much tighter syncline at the termination of the underlying Simano nappe.

At least as important as improving structural maps, modeling the seismic data indicates that it is necessary to incorporate additional units to account for the observed reflections; some of these units are not expected to be present from surface considerations alone. As discussed above, the Chiavenna ophiolite probably continues in the subsurface substantially farther north than previously realized, and some 3 km of additional material (Gruf or Bündnerschiefer) is likely present between it and the Adula nappe. Incorporating these units as well as layers corresponding to the Aul and Simano nappes and the basal Penninic thrust provides a reasonably complete picture of large-scale upper crustal structure.

Three-Dimensional Effects and Migration

Migration of the seismic data is an alternate method to produce a subsurface model. In this case, however, the three-dimensional structure presents difficulties for migration. Some reflections emanate from points that are up to 5 km away from the line, and depths to reflection points differ by as much as 3 km from depths beneath shot points, as depicted by Figure 5. If this effect were not considered, depth estimates derived from seismic travel times would be in error by up to 1 km. Furthermore, since the strike and dip of the structures change, these effects vary widely, depending upon both depth and position along the line; that is, reflections may issue from as far as several kilometers to either the north, west, or south. These circumstances render two-dimensional migration incapable of repositioning most reflections to their proper location. In addition, small bodies of different lithologic units, which may be of various depths, orientations and distances from the seismic line, are certainly present in the subsurface [Pfiffner et al., 1991]. Many of these features are likely to be effective point or line diffractors, scattering energy to various positions on the seismic line. These off-line diffractions cannot be fully collapsed by migration, as discussed above. Moreover, migration results may be misleading since sideswipe reflections will be repositioned to somewhere along the line, leading to a possible interpretational pitfall. These facts suggest that a modeling-based interpretation of unmigrated data is perhaps the most effective strategy when three-dimensional structures are involved.

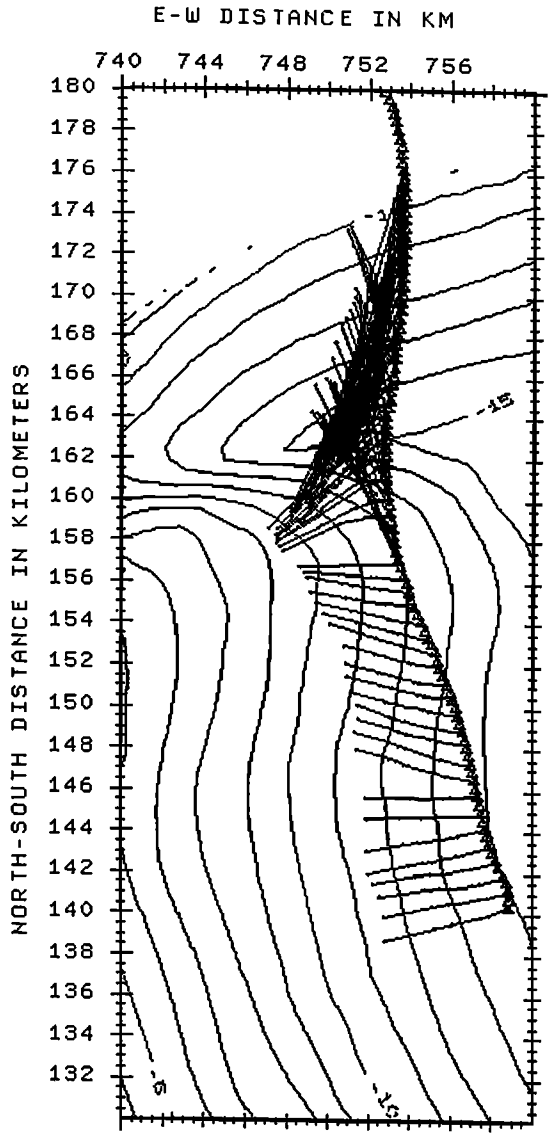

Fig. 5. Contour map of the base of the Adula nappe showing normal incidence ray paths from seismic line to reflection points projected onto horizontal plane. Contours are in kilometers below sea level. Note variation in ray path direction and distance from surface location of seismic line. Reflection points depict the downdip limit of seismic control.

Reflectivity, Lithology, and Basement Faults

Physical properties measurements indicate that interfaces of high-impedance carbonates, metacarbonates, and ophiolites with lower-impedance schists and gneisses should produce strong reflections [Sellami et al., 1990]. Modeling results indicate that surface exposures of many of these interfaces project to locations corresponding to strong reflections on the seismic data. Thus we infer that strong reflection segments can reasonably be associated with pods of ophiolites or carbonates juxtaposed against schists or gneisses. Many of these reflection segments, in fact, exhibit a one-to-one correspondence with specific mapped exposures, for instance, in the Aul nappe and Splügen zone. In contrast, mylonitic shear zones, in and of themselves, do not appear to be responsible for the stronger reflections. Measurements of mylonitized versus nonmylonitized samples of both the Tambo and Suretta nappes indicate a reflection coefficient of only 0.01 versus 0.06 - 0.09 for carbonate/gneiss interfaces [Sellami et al., 1990]. Tuning of thin beds may enhance some reflections but probably only supplies a modest contribution toward increasing amplitudes [Spaargaren and Warner, 1991]. The conclusion that strong reflections in the Penninic Alps are primarily due to first-order lithologic contrasts is consistent with several recent studies ascribing strong crustal reflections to changes in lithology elsewhere [e.g., Pratt et al., 1991; Litak and Hauser, 1992; Parsons et al., 1992].

Marked variations in amplitude are also most easily explained as due to discontinuous carbonate and ophiolitic lenses, similar to those observed at the surface. The ability to locate and define these second-order features contributes to more comprehensive mapping of the subsurface [Pfiffner et al., 1991]. One area where amplitude variations are especially evident is along the basal Penninic thrust. Following the suggestion of Sellami et al. [1990], we interpret the strong reflection from 3.2 to 4.0 s near CMP 1500 as autochthonous carbonates overlying Aar or Gotthard basement. Despite having accommodated substantial displacement, the basal Penninic thrust otherwise appears poorly reflective, perhaps indicating that acoustic impedance contrasts are lacking between the granitic Aar basement and the overlying gneisses of the Adula and Simano cores. This emphasizes that caution must be applied in interpreting the reflection geometry of basement faults.

Material Balance Considerations

The existence of an imbricated stack of upper-crustal basement nappes requires that substantial shortening has taken place in the Penninic zone. However, the magnitude of shortening is difficult to quantify, partly because complex polyphase deformation has created three-dimensional structures for which it is inappropriate to attempt to construct balanced cross sections [e.g., Pfiffner et al., 1990*a*]. The shortening amount is important to ascertain because it is one of two key constraints (the other being original crustal thickness) on the amount of "missing" lower crust that must be accounted for in some manner. This study may be considered an initial step toward assessing the three-dimensional nappe geometry on a crustal scale. Success in identifying nappe surfaces with reflections encourages the belief that collection of additional seismic data may eventually lead to volumetric material balance calculations. These, in turn, would shed considerable light on the question of whether and how much of the European lower crust has been subducted beneath the Alps, as suggested by Laubscher and Bernoulli [1982] among others.

CONCLUSIONS

A three-dimensional model constructed primarily from surface geological trends and physical properties measurements is able to reproduce the main reflection elements of the southern end of seismic line NFP20-EAST. Details evident on the seismic data, for instance, location of strong reflections, changes in dip, and "bow-tie" reflection patterns, are also present on the synthetic section. This result strongly supports the interpretation of reflections throughout the upper crust of the Penninic Alps in eastern Switzerland as chiefly due to surfaces of basement nappes and thin zones of associated sedimentary cover rocks. This model of first-order structure thus constitutes the most complete and well-constrained three-dimensional representation of the Penninic upper crust available to date. As such, it should serve as a productive starting point in facilitating attempts to reconstruct the pre-Alpine European margin.

Knowing the reflection coefficients of reflectors (from laboratory measurements) and their geometry (from modeling of projected surface trends) permits the identification of simple lithologic variations as the primary cause of the observed reflections. Thin zones of carbonates or ophiolites between gneissic basement units are particularly important reflectors. Reflection coefficients of 0.05 - 0.10, possibly enhanced by tuning in some cases, apparently produce quite strong reflections. In this area, major faults and shear zones make only minor contributions to overall reflectivity, except where they juxtapose differing lithologies.

The interpretational strategy of correlating subsurface reflection patterns with outcropping geology, which can be greatly facilitated by modeling, is particularly applicable in the Alps, so well exposed and long studied by both geologists and geophysicists. These results help to enhance the ability to correlate deep reflections with specific lithologies and structures, an important step in advancing understanding of both Alpine tectonics and the nature of basement reflections.

Acknowledgments. Data were collected under the auspices of the Swiss National Research Program NFP-20; initial processing including demultiplexing and line geometry was carried out by ETH (Zurich). Litak was partly supported by an Amoco Foundation Doctoral Fellowship; the U. S. National Science Foundation grants EAR 89-16129 and INT 89-22503 also provided financial support. T. Chaimov, M. Barazangi, J. Oliver, and *Tectonics* referees D. Snyder and H. Thybo contributed helpful reviews of the manuscript. Sierra Geophysics provided modeling software. Institute for the Study of the Continents contribution 168.

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(Received April 16, 1991;
revised February 5, 1993;
accepted February 5, 1993.)