Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps

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Abstract. A complete Alpine cross section integrates numerous seismic reflection and refraction profiles, across and along strike, with published and new field data. The deepest parts of the profile are constrained by geophysical data only, while structural features at intermediate levels are largely depicted according to the results of three-dimensional models making use of seismic and field geological data. The geometry of the highest structural levels is constrained by classical along-strike projections of field data parallel to the pronounced easterly axial dip of all tectonic units. Because the transect is placed close to the western erosional margin of the Austroalpine nappes of the Eastern Alps, it contains all the major tectonic units of the Alps. A model for the tectonic evolution along the transect is proposed in the form of scaled and area-balanced profile sketches. Shortening within the Austroalpine nappes is testimony of a separate Cretaceous-age orogenic event. West directed thrusting in these units is related to westward propagation of a thrust wedge resulting from continental collision along the Meliata-Hallstatt Ocean further to the east. Considerable amounts of oceanic and continental crustal material were subducted during Tertiary orogeny, which involved some 500 km of N-S convergence between Europe and Apulia. Consequently, only a very small percentage of this crustal material is preserved within the nappes depicted in the transect. Postcollisional shortening is characterized by the simultaneous activity of gently dipping north directed detachments and steeply inclined south directed detachments, both detachments nucleating at the interface between lower and upper crust. Large scale wedging of the Adriatic (or Apulian) lower crust into a gap opening between the subduced European lower crust and the pile of thin upper crustal flakes (Alpine nappes) indicates a relatively strong lower crust and detachment between upper and lower crust.

Introduction

Plate 1 integrates geophysical and geological data into one single cross section across the eastern Central Alps from the Molasse foredeep to the South Alpine thrust belt. The N-S section follows grid line 755 of the Swiss topographic map (except for a southernmost part near Milano, see Figure 1 and inset of Plate 1). As drawn, there is a marked difference between the tectonic style of the shallower levels and that of the lower crustal levels. This difference in style is only partly real. The wedging of the lower crust strongly contrasts with the piling up and refolding of thin flakes of mostly upper crustal material (the Alpine nappes), particularly in the central portion of the profile. This contrast is probably the most spectacular and unforeseen result of recent seismic investigations in the framework of the European Geotraverse (EGT) and the National Research Program on the Deep Structure of Switzerland (NFP 20). Partly, however, this difference in style reflects the different types of data used for compiling this integrated cross section. Upper crustal levels have been drawn on the basis of projected surface information, locally constrained by the results of geophysical modeling (parts of the northern foreland and the Penninic nappes). The geometry of the lower crustal levels, on the other hand, relies entirely on the results of deep seismic soundings which have a different scale of resolution. As a result, lower and upper crustal levels may look more different in style and therefore less related than they probably are.

Deformation certainly was not plane strain within this N-S-section. Shortening, extension, and displacements repeatedly occurred in and out of the section. Faults with a strike-slip component, such as, for example, the Periadriatic (Insubric) line, currently juxtapose crustal segments, the internal structures of which may have developed somewhere else. Because this contribution is primarily aimed at a discussion of Plate 1, it will strongly focus on the cross-sectional view. However, the three-dimensional problem [*Laubscher*, 1988, 1991] will be repeatedly addressed.

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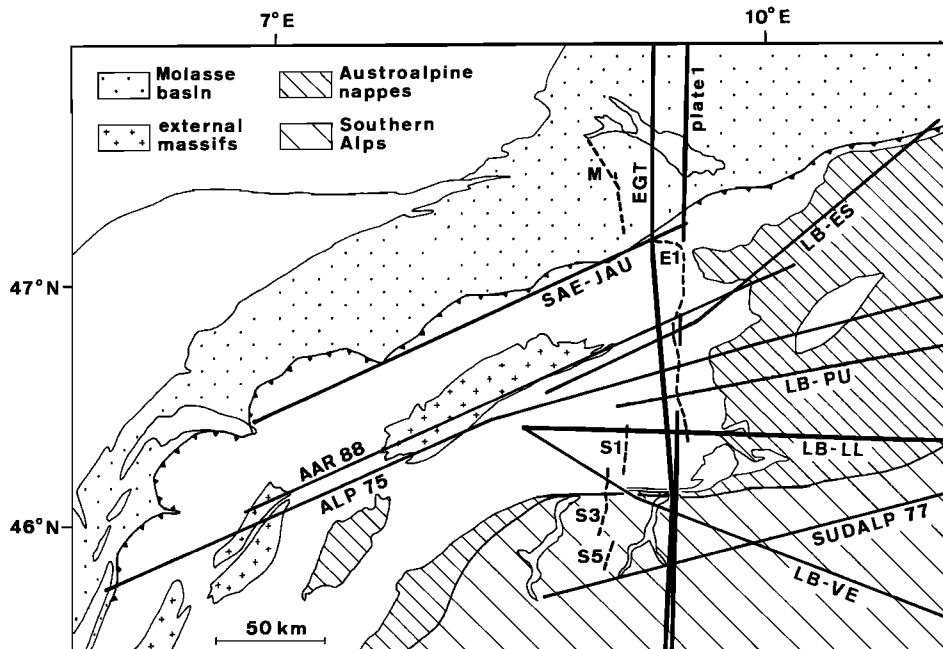
Figure 1. Network of seismic lines used for constraining the profile of Plate 1. Solid lines are refraction profiles; broken lines are reflection profiles.

The transect of plate 1 closely follows the EGT profile and line E1 of the NFP 20 project (Figure 1, inset of Plate 1). The area around this transect probably represents the best-investigated part of a collisional orogen worldwide, both from a geophysical and geological point of view. Geologically, its position is ideal: it follows closely the N-S running western erosional margin of the Austroalpine units of the Eastern Alps, which are missing further to the west and which almost completely cover lower structural units further to the east (Figure 1, inset of Plate 1). This allows for the projection of the Austroalpine units into the profile. This procedure enlarges considerably the cross section in a vertical direction: in the southern Penninic units, downward extrapolation using geophysical data to depths of about 60 km can be complemented by an upward projection reaching 20 km above sea level.

Methods and Data Used for the Construction of the Integrated Cross Section

The different parts of the cross section have been obtained by a variety of different construction and projection methods. These methods, as well as the nature and quality of the geological and geophysical data, need to be outlined briefly for a better appreciation of the assumptions underlying the construction and the nature of the data sources.

Geophysical Data

The solid lines labeled "crustal model along EGT" (Plate 1) denote the position of the upper and lower boundary of the lower crust which is generally characterized by a significant increase in the P wave velocity and often high reflectivity. In the profile of Plate 1 the position of these interfaces of the lower crust is drawn after the results of refraction work [Ye, 1992; Buness, 1992] and an integrated interpretation of both refraction and reflection seismic data [Holliger and Kissling, 1992]. This allows the reader to assess the degree of compatibility with the results obtained by the reflection method, also displayed in Plate 1. The positions of these interfaces depicted in Plate 1 do not differ significantly from those given by Valasek [1992]. Positions where the interfaces are not well constrained by the data are indicated by broken lines. Only well-constrained seismic velocities from Ye [1992] are indicated in Plate 1 where they do not spatially overlap with the drawing of geological features. Velocities of around 6.5 to 6.6 km s^{-1} typical for the lower crust (with a notable exeption for the lower crust in the northern foreland) (according to Ye [1992]), contrast with values between 6.0 and 6.2 km s^{-1} in the lower parts of the upper crust. Layers characterized by lower velocities than those indicated in Plate 1, including velocity inversions, are observed at shallower depths [Ye, 1992]. Low-velocity layers (about 5.8 km s^{-1}) are found beneath the external Molasse basin, within the lower Penninic nappes, and

underneath the Southern Alps [*Mueller*, 1977; *Mueller et al.*, 1980; *Ye*, 1992] at a depth of about 10 km. The solid lines denoting the interfaces of the lower crust are constrained by migrated wide-angle reflections (modified after *Holliger and Kissling* [1992] and *Ye* [1992]). The position of these reflections is very strongly controlled by seven refraction profiles oriented parallel to the strike of the chain (Figure 1) (see also *Holliger and Kissling* [1991, 1992] and *Baumann* [1994]). All these profiles intersect the profile of Plate 1 and the EGT refraction profile [*Ye*, 1992]; hence there is considerable three-dimensional control on the position of the reflectors. The depth migration procedure within the EGT profile (almost identical with the cross section of Plate 1) integrates new data by *Ye* [1992] and is outlined by *Holliger* [1991] and *Holliger and Kissling* [1991, 1992].

We chose to superimpose the results of reflection seismic work directly onto the features arrived at by refraction seismics in order to graphically visualize the degree of compatibility between these two data sets. Major deep reflections from the E1, S1, S3, and S5 lines (Figure 1) have been converted into digitized line drawings by a procedure outlined by *Holliger* [1991]. These digitized line drawings have been projected into the EGT line before migration in the N-S section. The eastward projection of data from the S1, S3, and S5 lines was necessary in order to complete the profile along the eastern transect (E1), which terminates well north of the Insubric line. The chosen procedure for eastward projection is described by *Holliger* [1991] and *Holliger and Kissling* [1991, 1992], who argued that the geometry of middle to lower crustal material is approximately constrained by Bouguer gravity data (corrected for the effects of the Ivrea body) [*Kissling*, 1980, 1982]. This projection procedure guided by gravity data then ultimately (i.e., after migration) leads to the configuration depicted in Plate 1. The procedure chosen is supported by independent evidence for the existence of a large lower crustal wedge from the refraction work carried out along the EGT line [*Ye*, 1992] and, additionally, the compatibility of the refraction-based model of *Ye* [1992] with the projected and migrated line drawings of the major reflectors as seen in Plate 1.

In a second step, the projected digitized line drawings were migrated according to a velocity model which needs no projection since it is based on strike-parallel profiles [*Holliger*, 1991]. This velocity model (Figure 4 of *Holliger and Kissling* [1992]) is the same as that used for the migration of the wide-angle reflections discussed earlier. The picture emerging from this procedure shows excellent consistency between refraction and reflection data and one geological feature which can be traced to great depth: the Insubric line.

Except for a reflectivity gap beneath the internal Aar massif and the Gotthard "massif", there is excellent

agreement between the position of the lower crust of the northern European foreland derived from refraction work (solid lines in Plate 1) and the zone of high reflectivity. The reason for this gap in the near-vertical reflection profile is not clear, but it is unlikely to represent a gap in the European Moho as postulated by *Laubscher* [1994]. Wide-angle data from the EGT profile and from several orogen-parallel profiles (Figure 1) show strong seismic phases from the Moho in this region [*Kissling*, 1993; *Ye et al.*, 1995], whose position is indicated by a solid line in Figure 2a [*Holliger and Kissling*, 1991]. By applying a normal move out (NMO) correction, *Valasek et al.* [1991] displayed these wide-angle Moho reflections along the EGT profile in a manner commonly used for near-vertical reflection data (Figure 2b). Hence Figure 2 clearly documents the continuity of the Moho beneath the northern foreland. The European lower crust may safely be extended as far south as beneath the northern rim of the Southern Alps where its presence has also been recorded along seismic lines provided by the Italian Consiglio Nazionale delle Ricerche (CROP-Alpi Centrali) [*Cernobori and Nicolich*, 1994; *Montrasio et al.*, 1994].

Plate 1 also depicts a wedge of Adriatic lower crust at a depth of 22 to 48 km beneath the Penninic nappes and above the European lower crust. The solid lines denoting the crustal model along the EGT traverse suggest that this wedge is continuous with the Adriatic lower crust beneath the Southern Alps. This simple geometry may represent an oversimplification caused by the low resolution of the geophysical data at this depth. First, the northern tip of this Adriatic wedge is ill-constrained (broken line in Plate 1). Second, its internal structure is likely to be more complicated due to imbrications within the wedge. The northward thickening of the Adriatic lower crust within this wedge cannot reflect a preorogenic feature since the northern extension of the crust beneath the Southern Alps is likely to have been attenuated during passive continental margin formation. According to the interpretations by *Cernobori and Nicolich* [1994], *Marson et al.* [1994], and *Montrasio et al.* [1994] the Moho of the Adriatic lithosphere is wedged beneath the northern part of the Southern Alps, rather than being continuous as depicted in Plate 1. *Holliger and Kissling* [1992] propose a mixture of predominantly Adriatic lower crust and oceanic crust within the Adriatic wedge, having a density slightly higher than that of "normal" lower crust. The reflections from the lower crustal Adriatic wedge shown in Plate 1 cross each other in many places. This may indicate discontinuities within the wedge, or, alternatively, it represents artifacts caused by the projection and/or migration procedure. In view of all these uncertainties regarding the internal structure of the Adriatic lower crustal wedge, Plate 1 merely depicts its outlines in a
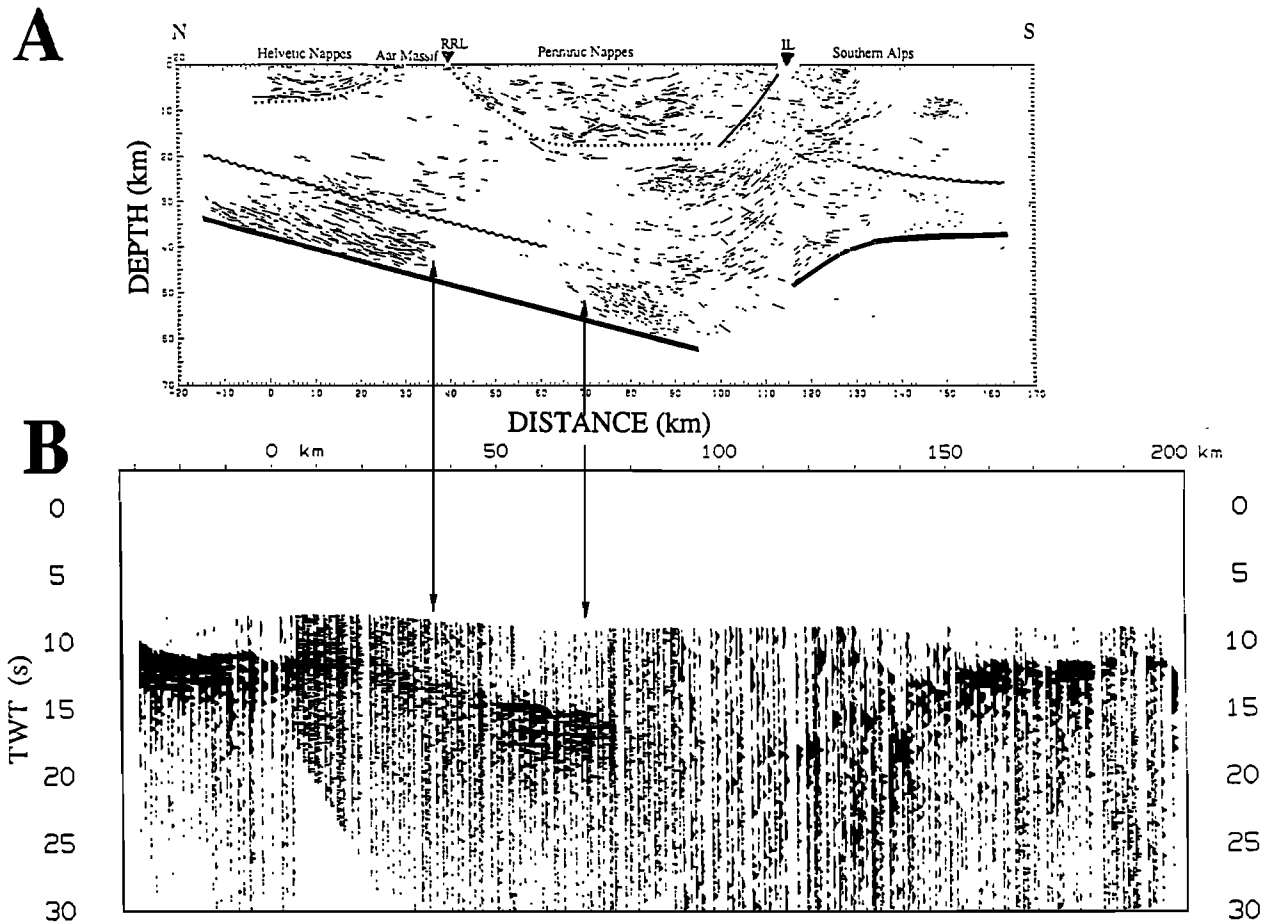
Figure 2. Summary of seismically determined crustal structure and Moho depth along the transect of Plate 1. Horizontal and vertical scale are the same in both panels. (a) Migrated near-vertical reflections along the eastern traverse and generalized seismic crustal structure derived from orogen-parallel refraction profiles [*Holliger and Kissling*, 1992]. Solid line indicates position of Moho, derived from orogen-parallel refraction profiles; wiggly line indicates top lower crust; dotted line indicates base of Penninic and Helvetic nappes; thin solid line is the Insubric line; RRL is the Rhine-Rhone line. (b) Normal-incidence representation of the wide-angle Moho reflections in the EGT (European Geotraverse) refraction profile perpendicular to the orogen and across the eastern Swiss Alps [*Valasek et al.*, 1991].

schematic way. It is clear from the compilation on Plate 1, however, that the Adriatic wedge represents a zone of high reflectivity, largely contained within the outlined shape of this wedge except for some gently north dipping reflections at a depth of 20-25 km, slightly above the upper boundary of the wedge as defined by refraction work (solid line below grid line 140 in Plate 1).

Reflections recorded along line S1, dipping with about 45° to the north after migration, are related to the Insubric line [*Bernoulli et al.*, 1990; *Holliger*, 1991; *Holliger and Kissling*, 1991, 1992]. In Plate 1 these reflections project into a surface location 5-10 km north of the Insubric line within the northern part of the southern steep belt, near the axial trace of the Cressim antiform. This southern steep belt is parallel to and related to

the Insubric mylonite belt [*Schmid et al.*, 1989]. Hence these reflections also document a flattening of the Insubric mylonite belt from the inclination of 70° measured at the surface [*Schmid et al.*, 1987, 1989] to about 45° at some 20 km depth.

Helvetic Nappes and Northern Foreland

The top of basement along the profile of Plate 1 is only accessible to surface observation in the Vättis window (Aar massif). The geometry chosen for the structure of the top of basement is that of model 1, discussed by *Stäuble and Pfiffner* [1991b]. These authors evaluated the seismic responses of four alternative geometries (models 1-4) generated by 2-D normal-incidence and off-set ray tracing with the reflection seismic data. They

produced the best-matching events with this particular model 1. Thrusts and folds in the Subalpine Molasse are constructed on the basis of surface data and projected information obtained along a seismic profile, recorded for hydrocarbon exploration, situated immediately west of the EGT traverse (profile M in Figure 1) [*Stäuble and Pfiffner*, 1991a].

The structure of the Helvetic nappes is constrained by the extrapolation of surface information obtained along the profile trace and by the results of 3-D seismic modeling [*Stäuble et al.*, 1993]. The higher Penninic and Austroalpine units overlying the Helvetic nappes are only exposed east of the transect and have been projected onto the profile parallel to a N 70° E azimuth by using profiles published by *Allemann and Schwizer* [1979] and *Nänny* [1948]. Updoming of the base of the Austroalpine nappes above the Aar massif corresponds to the Prättigau half window in map view (Figure 3). Its geometry was obtained by the stacking of a series of profiles across the Prättigau half window [*Nänny*, 1948]. Stacking did not use a fixed axial plunge but instead resulted from lateral correlation between individual profiles. The geometry thus obtained (Plate 1) results in an average plunge of 15° to the east for the culmination of the base of the Austroalpine units, in accordance with the seismically constrained axial plunge of the Aar massif [*Hitz and Pfiffner*, 1994].

The Gotthard "Massif" and the Transition into the Lower Penninic Nappes

Very strong reflections dipping southward from 2.5 to 4.0 s two-way travel time (TWT) along line E1 between Canova and Thusis (reflector D in Plate 4 of *Pfiffner et al.* [1990b]) have been interpreted in Plate 1 (between grid lines 175 and 190) to be due to the allochthonous cover of the southern Gotthard "massif" [*Etter*, 1987]. The Penninic basal thrust is placed immediately above the inferred allochthonous cover of the Gotthard "massif" (labeled "Triassic, Lower, and Middle Jurassic cover slices" in Plate 1) according to the model of the Penninic units given by *Litak et al.* [1993]. Earlier interpretations based on north dipping reflectors visible under the Gotthard "massif" (northern termination of reflector E in Plate 4 of *Pfiffner et al.* [1990b]), advocating back thrusting and/or back folding of the Gotthard massif (model C of *Pfiffner et al.* [1990b]), are abandoned.

According to the geological interpretation given in Plate 1, the basal thrust of the Gotthard "massiv", situated in the Urseren-Garvera zone, is steeply inclined and would therefore not be imaged seismically. The Penninic basal thrust is not shown to be strongly back folded but merely steepened in Plate 1, based on the geometry constrained by 3-D seismic modeling (Figure 3a of *Litak et al.* [1993]). This indicates a substantial

change in structural style in respect to profiles further to the west [*Etter*, 1987; *Probst*, 1980]. There (Lukmanier area) a major back fold (Chiera-synform, Figure 4) (D3 of *Etter* [1987]) formed south of the Gotthard "massif". Such back folding is even more pronounced in the southern part of the external massifs in western Switzerland [*Escher et al.*, 1988]. This severe overprint by back folding apparently dies out eastward.

The Gotthard "massif" is considered as a lowermost Penninic, or more exactly a "Subpenninic" nappe [*Milnes*, 1974], in the structural sense. These Subpenninic units also include the Lucomagno-Leventina and Simano nappes, whose geometry will be discussed later. There is a serious problem with the use of terms like "Helvetic" and "Penninic" in that, for historical reasons going back to *Argand* [1916], they usually refer to paleogeographic domains and/or structural units. Whereas the Lucomagno-Leventina and Simano nappes and, according to our interpretation, also the Gotthard "massif" may be described as Penninic in terms of structure and metamorphism, it is very likely that some of this crystalline basement represents basement to the Helvetic and Ultrahelvetic cover nappes. This is supported directly by the facies of the overturned allochthonous cover of the southern Gotthard "massif" [*Etter*, 1987, and references therein], which has close affinities with the Helvetic sediments. Use of the term "Subpenninic" helps to resolve this dilemma.

To the west of our transect the Tavetsch massif (a small external massif south of the Aar massif) represents the substratum of the Helvetic Axen nappe, while the Gotthard "massif" represents the substratum of the higher Säntis-Drusberg nappe according to *Pfiffner* [1985] and *Wyss* [1986]. Within the transect of Plate 1, the structural separation amongst individual Helvetic nappes above the Glarus is less severe. In the profile considered here, the Säntis thrust separates the Jurassic strata of the Lower Glarus nappe complex from the Cretaceous strata of the Upper Glarus nappe complex [*Pfiffner*, 1981]. The Säntis thrust acted as a structural discontinuity separating different styles of shortening within the Jurassic and Cretaceous strata. Displacement across the Säntis thrust decreases steadily southward and eastward due to imbrications in the Jurassic strata [*Stäuble et al.*, 1993]. Bed length measured in the Upper Jurassic limestone (38 km) is similar to that measured in the Cretaceous Schrattenkalk (33 km). Hence both stratigraphic levels must be assigned to the same basement, contrarily to the findings further west.

This leads to the question if the entire Glarus nappe complex has to be rooted in the Tavetsch massif [*Trümpy*, 1969] or, alternatively, within the Subpenninic nappes. We prefer the second option in view of the considerable difficulties of finding appropriate volumes of upper crustal basement material in the very small Tavetsch
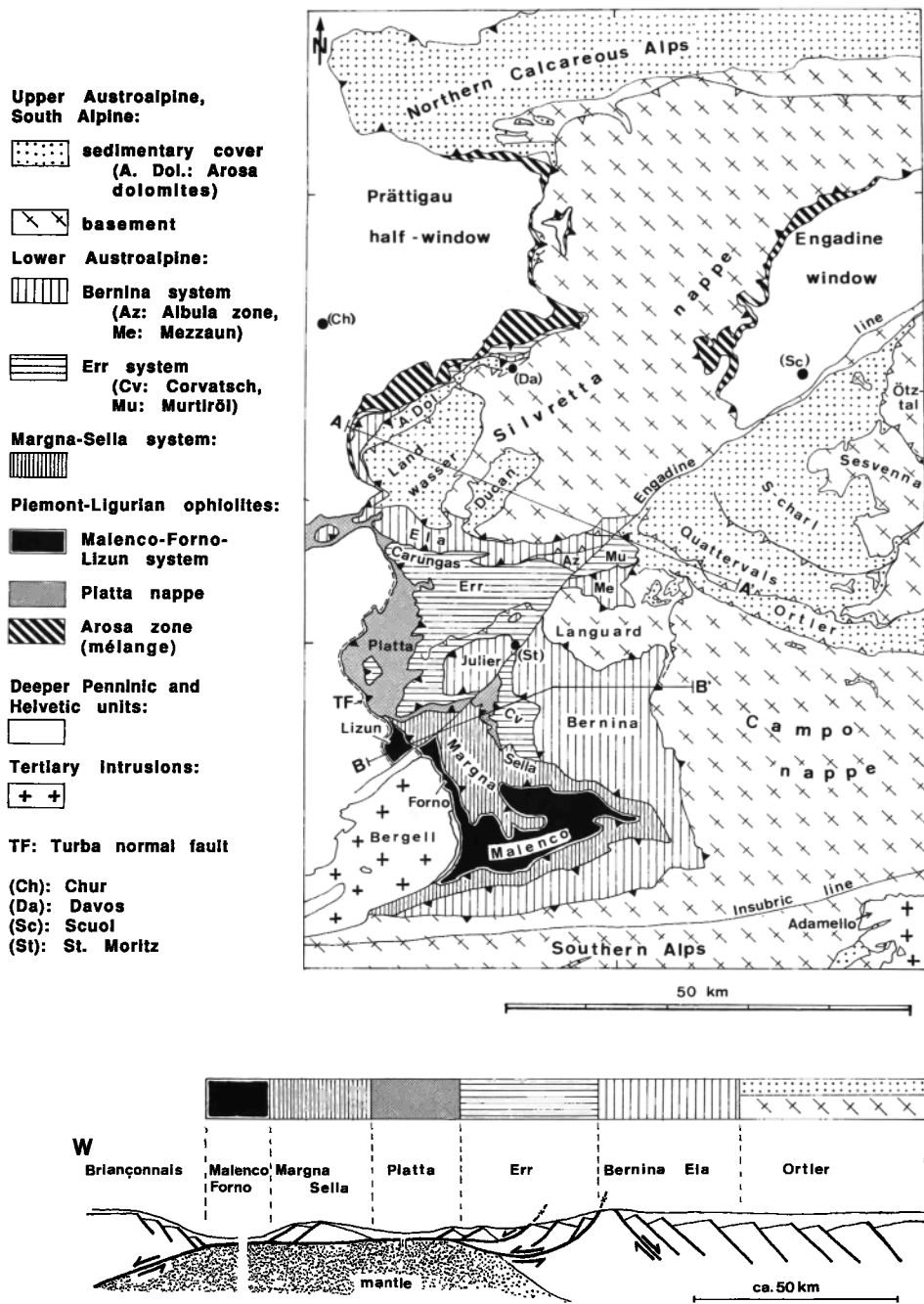
Figure 3. Tectonic map of eastern Switzerland, modified after *Schmid et al.* [1990]. Circled numbers in inset refer to ophiolite-bearing units (solid areas) derived from the South Penninic or Piemont-Liguria Ocean (units labeled "1") and from the North Penninic or Valais Ocean (units labeled "2"). Numbers indicate the following: 1a, Arosa; 1b, Platta; 1c, Lizun and Avers; 1d, Malenco; 2a, Chiavenna; 2b, Misox zone; 2c, ophiolites within North Penninic Bündnerschiefer; 2d, Areue-Bruschghorn; 2e, Martegnas. Profile trace refers to the the profile of Plate 1.

massif. In map view, the Tavetsch massif pinches out eastward and is unlikely to be encountered in the transect of line E1. The excess volume of upper crust provided by the updoming of the Aar massif is ruled out from the search for appropriate basement material.

This excess volume is caused by some 27 km of crustal shortening postdating the detachment of the Helvetic nappes and related to imbrications in the Subalpine Molasse [*Burkhard*, 1990; *Pfiffner*, 1986; *Pfiffner et al.*, 1990b]. In order to accommodate the 38 km bed length

Figure 4. Correlation table showing an attempt to date deformation phases and metamorphism along the transect of Plate 1. Timescale is according to *Harland et al.* [1989]. The abbreviations UMM, USM, OMM, and OSM denote the Lower Marine Molasse, Lower Freshwater Molasse, Upper Marine Molasse, and Upper Freshwater Molasse, respectively. See text for further explanations. For an extensive discussion, see *Schmid et al.* [1996].

of Helvetic nappes (assuming plane strain conditions and an upper crustal thickness of 15 km), an area of about 570 km² of upper crustal material has to be located somewhere in Plate 1. This suggests that both the crystalline basement of the Gotthard "massif" and the Lucomagno-Leventina nappe (occupying about 540 km² in our section) may represent this upper crustal basement of the Helvetic and Ultrahelvetic nappes.

The Northern and Central Parts of the Penninic Zone

In a first step, all major tectonic boundaries (Figure 3) have been projected strictly parallel to a N 70° E direction up and down plunge. This direction approximates best the azimuth of most large-scale fold structures in this region. A series of sections parallel to

N 70° E, constructed on the basis of structure contour maps, allowed for projections with variable plunge (10°-35°). Units were projected into the section along these strike-parallel sections by assuming that their thickness does not change along strike. Geological details within projected units are drawn according to the geometries found where these units are exposed (for a recent compilation of field data, see *Schmid et al.* [1996]).

In a second step this part of the profile was adjusted to conform to the 3-D model based on seismic information [*Litak et al.*, 1993]. These adjustments were relatively minor at shallower depths and above the Adula nappe. The most important modification concerns the Misox zone, which has a considerable thickness and which is shown to be continuous toward the south, joining up with the Chiavenna ophiolites (Figure 3) exposed

at the surface. This is in contrast to surface geology exposed west of the profile, where the Misox zone is cut out between the Adula and Tambo nappes due to top-east movements along the Forcola normal fault (Figure 3). In Plate 1 the Chiavenna ophiolite is portrayed as a long continuous slab, about 1 km thick, which caused high-amplitude reflections [*Litak et al.*, 1993].

The overall geometry of the Adula and Simano nappes follows that given in Figure 3a of *Litak et al.* [1993]. Ornamentation in the Adula nappe is based on the data of *Löw* [1987]. A considerable amount of speculation led to the depicted geometry of the top of the Gotthard "massif" and the Lucomagno-Leventina units. While their overall position below the Penninic basal thrust is constrained by the model of *Litak et al.* [1993], the portrayed structural details are based on surface information a long way west of the transect. This information, which was taken from profiles by *Etter* [1987], *Löw* [1987], and *Probst* [1980], had to be modified significantly in order to conform to the constraints imposed by the geometry of the Penninic basal thrust. As seen from Plate 1, there is no room for additional Subpenninic thrust sheets between the Lucomagno-Leventina nappe and the Adriatic lower crustal wedge. However, such lower units do in fact exist along the S3 line [*Bernoulli et al.*, 1990], but they are interpreted to wedge out eastward.

Southern Penninic Zone, Bergell Pluton, and Insubric Line

In the area of the Bergell (Bregaglia) pluton [*Trommsdorff and Nievergelt*, 1983] the profile is based on recent work by *Rosenberg et al.* [1994, 1995], *Berger et al.* [1996], and *Davidson et al.* [1996]. In its northern part the Bergell pluton has been synmagmatically thrust onto the upper amphibolite to granulite grade migmatitic rocks of the so-called Gruf complex (Figure 3) [*Bucher-Nurminen and Droop*, 1983; *Droop and Bucher-Nurminen*, 1984]. The Gruf complex finds its direct continuation in the migmatites forming the southernmost part of the Adula nappe [*Hafner*, 1994], back folded around the Cressim antiform (Plate 1) [*Heitzmann*, 1975]. Therefore the Gruf complex, including a small window below the Bergell pluton (Figure 3), has to be considered part of the Adula nappe.

The quartzo-feldspatic gneisses predominating within the Gruf complex are overlain by a variety of other lithologies consisting of ultramafics, amphibolites, calcsilicates, and alumo-silicates, concentrated in an almost continuous band concordantly following the tonalitic base of the Bergell pluton exposed along the western margin [*Wenk and Cornelius*, 1977; *Diethelm*, 1989]. A narrow antiform within the Gruf complex immediately south of the Engadine line and north of the Bergell pluton (Figure 3, indicated in Plate 1 according to work

in progress) is interpreted to connect these lithologies at the base of the pluton with the Chiavenna ophiolites overlying the Gruf complex along a steeply north dipping faulted contact [*Schmutz*, 1976]. Hence this band of ultramafics and metasediments found on top of the Gruf complex is interpreted to be the southern continuation of the Chiavenna ophiolite and the Misox zone representing the suture zone of the north-Penninic ocean (Figure 3). Recent mapping revealed that the granodiorite discordantly cuts through the remnants of both Tambo and Suretta nappes situated south of the Engadine line. This results in the geometry shown in Plate 1: In profile view the Bergell pluton occupies the structural position of the Tambo and Suretta nappes. Magmatic, submagmatic, and solid state deformational fabrics in tonalite, granodiorite, and country rocks show that the Bergell pluton was emplaced and solidified during a regional tectonic event as originally suggested by *Wenk* [1973]. This synmagmatic deformation first produced a very strong (locally mylonitic) fabric found at the base of the pluton and subsequently led to the large-scale folds that shortened this contact (Plate 1). One of these folds can be traced directly into the Cressim antiform (plate 1) [*Hafner*, 1994; *Davidson et al.*, 1996].

Initial stages of vertical movements along the Insubric mylonite belt affected the tonalitic tail of the southern Bergell pluton and were coeval with deformation in the presence of melts [*Rosenberg et al.*, 1994]. This shows that final intrusion, back folding, and initial stages of back thrusting along the Insubric line are contemporaneous and related to ongoing N-S shortening. Only the vertical, brittle Tonale fault [*Fumasoli*, 1974] is related to later strike-slip movements under brittle conditions along the Insubric line.

Considerable vertical extrapolation is possible thanks to the pronounced axial plunge of the Bergell pluton indicated by structural [*Rosenberg et al.*, 1994, 1995] and petrological [*Reusser*, 1987] data. In a first step, the Tambo and Suretta nappes were projected southward and upward by using structure contour maps [*Pfiffner et al.*, 1990a], partly modified by new field data. At a point situated near Vicosoprano, east of the transect (projecting well above sea level in Plate 1), the boundaries of Tambo, Suretta, and overlying nappes were displaced vertically across the Engadine line by 4 km, in accordance with the kinematic model for this line proposed by *Schmid and Froitzheim* [1993]. With this procedure the position of the Tambo and structurally higher tectonic units was anchored to their position immediately south of the Engadine line.

The position of the base of the Bergell intrusion was evaluated by projecting auxiliary profiles located east of Plate 1. This projection used structure contour maps [*Davidson et al.*, 1996] of the base of the pluton, deformed by NE-SW striking folds. The roof of the intru-

sion was placed at the structural level presently exposed at the eastern margin of the pluton. This is a minimum altitude, since the eastern contact represents the side rather than the roof of this pluton [*Spillmann*, 1993; *Rosenberg et al.*, 1995; *Berger and Gieré*, 1995]. The geometry of the "Ultrapenninic" (in the sense of *Trümpy* [1992]) or Austroalpine Margna and Sella nappes, as well as the continuation of the southward outwedging Platta ophiolites and the Corvatsch-Bernina nappes, is drawn after *Liniger* [1992] and *Spillmann* [1993] in Plate 1.

Southern Alps

The Southern Alps part of the section was taken without modification from *Schönborn* [1992, cross section B of the enclosure] except for the northernmost part where compatibility with the shape of the Insubric fault necessitated very minor adjustments. This section of *Schönborn* [1992] almost exactly coincides with N-S grid line 755, departing from a N-S orientation only south of E-W grid line 60 in order to incorporate borehole data published by *Pieri and Groppi* [1981].

The profile is balanced and retrodeformability was established at all stages by forward modeling. The deeper parts of the profile were kept as simple as possible and drawn according to geometrical rules of ramp and flat geometry indicated for basement and cover by the surface data. The mass balance within the basement, the top of which is constrained by borehole data (Plate 1) in its undeformed portion in front of the Milan thrust belt and by the CROP-Alpi Centrali seismic profile [*Montrasio et al.*, 1994], is unaffected by geometrical details. The total amount of shortening (80 km) within the sediments necessarily leads to the postulate that parts of the upper crustal and all of the lower crustal excess volume must now occur within the Adriatic wedge situated below the Penninic nappes and the Insubric line. The volume of crustal material available south of the Insubric line is insufficient [*Schönborn*, 1992; *Pfiffner*, 1992]. In our view, substantial thinning of the Adriatic lower crust during the final stages of Jurassic rifting and continental margin formation cannot be held responsible for this volume deficit since we infer a lower plate margin situation for the Apulian margin (see later discussion).

In order to allow for a change in structural style within the deeper basement [*Milano et al.*, 1991], ductile shear zones have been schematically drawn at depth. These shear zones are expected to merge with a major detachment zone situated at the interface between upper and lower Adriatic crust. This major detachment allows for the northward indentation of the Adriatic lower crust or, conversely, for southward transport of the Insubric line, together with the Central Alps, over the Adriatic lower crust.

Summary of the Tectonic Evolution

Paleotectonic Structuration

Because the paleotectonic structuration strongly influences the later orogenic evolution, a brief discussion of our current working hypothesis is needed (see *Froitzheim et al.* [1996] for a more extensive discussion). The paleotectonic restoration in Figure 5 follows the traditional approach guided by stratigraphical analysis and retrodeformation of nappe stacks, taking into account effects of postnappe refolding. In most cases [e.g., *Frisch*, 1979; *Trümpy*, 1980; *Platt*, 1986] this classical approach leads to the postulate for the former existence of more than one paleogeographic domain of sediments deposited on oceanic crust and/or exhumed mantle (loosely referred to as "oceanic" in this contribution). However, recently, an alternative view, interpreting the internal zones of the Alps in terms of an orogenic wedge formed by subduction erosion and accretion [e.g., *Polino et al.*, 1990; *Hunziker et al.*, 1989], has been expressed. According to this hypothesis, interleaving of continental and oceanic crustal flakes is invariably due to tectonic complications, only one ocean being subducted within one trench between Europe and Apulia since Cretaceous times.

According to our reconstruction (Figure 5), three oceanic basins did open and close at different times in the Alps and the Western Carpathians: the Meliata-Hallstatt, the Piemont-Liguria (or South Penninic in the Swiss-Austrian Alps) and the Valais (or North Penninic) Oceans. While remnants of two of these oceanic domains, the Piemont-Liguria and Valais Oceans (mapped in Figure 3), are found in the form of ophiolitic slivers along the cross section of Plate 1, remnants of the Meliata-Hallstatt Ocean are only found further to the east (Eastern Alps of Austria, Carpathians). However, because this ocean played an important role during Cretaceous orogeny, it needs to be briefly discussed.

The Meliata-Hallstatt Ocean opened during the Middle Triassic in a position southeast of the Austroalpine realm [*Kozur*, 1992], and it may have been connected to the Vardar Ocean of the Dinarides and Hellenides. Its suture is indicated in the sketch of Figure 5. Triassic sediments of the Austroalpine units record the history of the shelf and passive margin of Apulia that faced this ocean [*Lein*, 1987]. Rifting that led to the opening of this Triassic ocean is spatially unrelated to the Late Triassic to Early Jurassic rifting leading to the opening of the Piemont-Liguria Ocean which will form at the northwestern margin of the Apulian microplate (western part of the Austroalpine nappes, Southern Alps). The remnants of the Meliata-Hallstatt Ocean did not reach the area of the profile of Plate 1. However, Cretaceous orogeny resulting from continental collision fol-
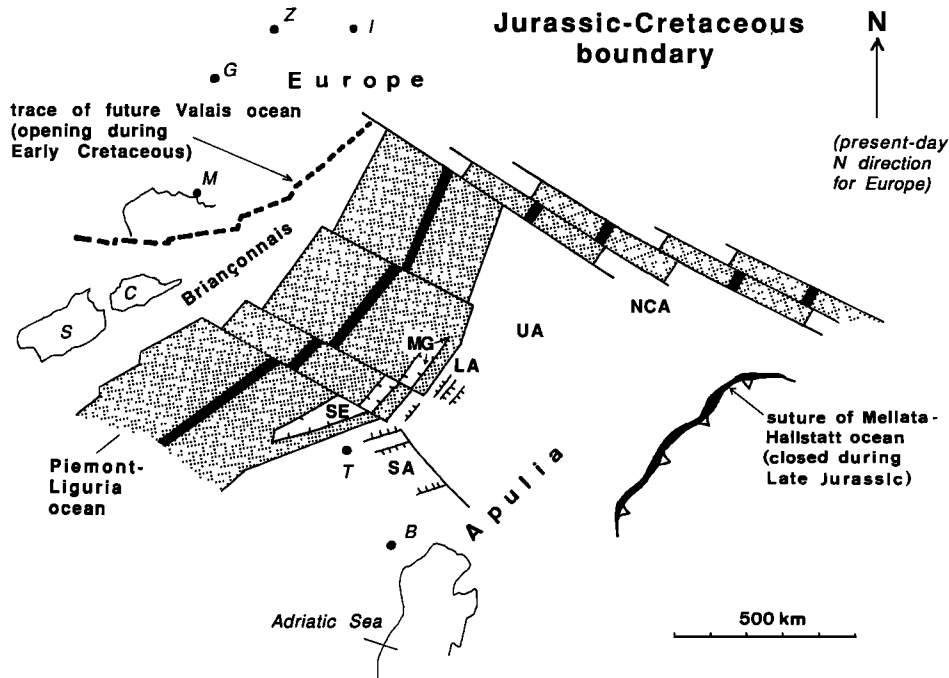
Figure 5. Paleogeographic reconstruction for the Jurassic-Cretaceous boundary, after *Dercourt et al.* [1986], *Stampfli* [1993], and *Schmid et al.* [1996], showing the oceanic suture of the former Meliata-Hallstatt Ocean, the Piemont-Liguria (South-Penninic) Ocean, and the trace along which the Valais (North-Penninic) Ocean will open. Abbreviations are SE, Sesia-Dentblanche extensional allochthon; MG, Margna extensional allochthon; SA, passive continental margin of Southern Alps; LA, Lower Austroalpine realm; UA, Upper Austroalpine realm; NCA, Northern Calcareous Alps. Geographical reference points are S, Sardinia; C, Corsica; M, Marseille; G, Geneva; Z, Zürich; I, Innsbruck; T, Torino; and B, Bologna.

lowing the closure of the Meliata-Hallstatt Ocean during the Early Cretaceous also affected the Austroalpine and South Penninic units in our transect. This collision was followed by westward propagation of a thrust wedge [*Thöni and Jagoutz*, 1993; *Neubauer*, 1994; *Froitzheim et al.*, 1994] toward the margin between Apulia and the South Penninic Ocean situated in the area of our transect.

Structures of the passive continental margin to the northwest of the Apulian microplate are locally well preserved in spite of crustal shortening in the Austroalpine nappes of Eastern Switzerland [*Froitzheim and Eberli*, 1990; *Conti et al.*, 1994] and in the Southern Alps [*Bertotti*, 1991; *Bertotti et al.*, 1993]. During the final rifting phase, related to the opening of the Central Atlantic (Toarcian to Middle Jurassic), a system of west dipping detachments formed [*Froitzheim and Manatschal*, 1996]. The passive margin preserved in the Austroalpine nappes of Graubünden (Figures 5 and 6) is amazingly similar to that preserved in the Southern Alps [*Bernoulli et al.*, 1993], and both areas exhibit features typical for a lower plate margin [*Lemoine et al.*, 1987; *Froitzheim and Eberli*, 1990]; however, see *Marchant* [1993] and *Trommsdorff et al.* [1993] for a differing view.

We suggest that the present Margna-Sella nappe system occupied a special position near the passive continental margin at the northwestern edge of the Apulian microplate (Figure 6). Following *Trümpy* [1992], we separated these "Ultrapenninic" units from the lower Austroalpine nappes with the Corvatsch-Bernina units at their base in the profile of Plate 1. According to *Froitzheim and Manatschal* [1996] the Margna-Sella nappes in Graubünden and the Dent Blanche-Sesia units of the Western Alps represent extensional allochthons that became separated from the Apulian margin by a narrow intervening zone of denuded mantle rocks (Platta unit in Plate 1) before the formation of a mid-oceanic ridge west of this extensional allochthon (Figures 5 and 6). The present structural position of the Margna-Sella nappes below the Platta ophiolites and above the Forno-Malenco ophiolites (Figure 7) [*Liniger*, 1992; *Spillmann*, 1993] is most readily explained with this hypothesis which does not call for an additional ocean or microcontinent.

The Briançonnais domain or terrane according to *Stampfli* [1993] is represented by the Tambo and Suretta nappes and detached sedimentary slivers (Schams, Sulzfluh, and Falknis nappes, Figure 3, Plate 1). According to many authors a last oceanic domain north of the
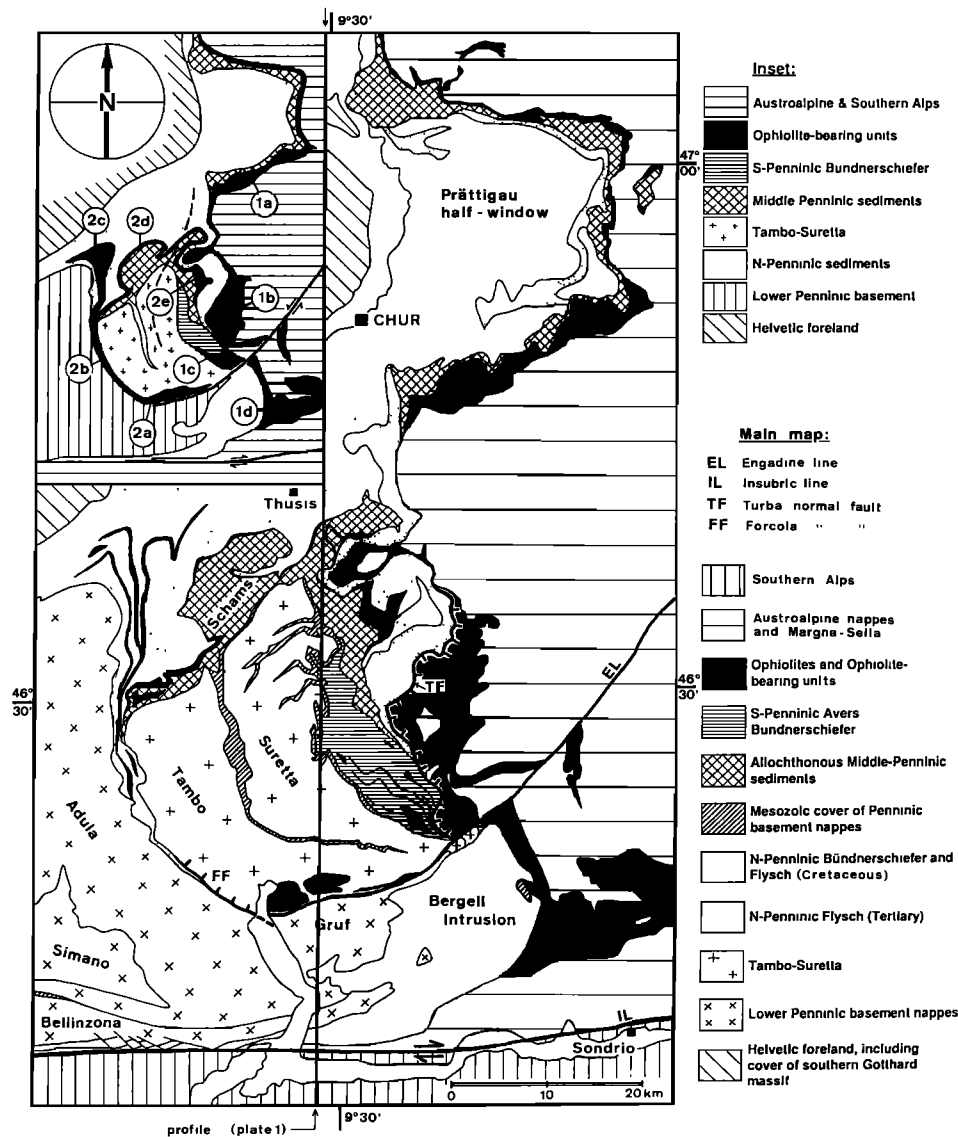
Figure 6. Reconstructed E-W section through the passive margin preserved in the Austroalpine units of Graubünden (bottom) (figure from *Froitzheim et al.* [1994]) and map of the tectonic units in the westernmost Austroalpine realm, representing westerly dislocated fragments of this passive continental margin. Small triangles along tectonic boundaries point in the direction of the structurally higher unit, irrespective of the nature of the boundary (thrust or normal fault) (for details, see *Froitzheim et al.* [1994]). A-A' and B-B' denote the profile traces of Figure 7.

Briançonnais terrane, the Valais Ocean, opened in the earliest Cretaceous [*Frisch*, 1979; *Florineth and Froitzheim*, 1994; *Stampfli*, 1993; *Steinmann*, 1994] due to gradual opening of the North Atlantic. The trace along which this new oceanic domain forms is depicted in Figure 5. In a westward direction the Valais Ocean is linked to opening in the Bay of Biscay and rifting in the area of the future Pyrenees [*Stampfli*, 1993]. The eastward continuation of this ocean is probably found within or near the northern margin of the preexisting South Penninic Ocean (Rhenodanubian flysch and Upper Schieferhülle of the Tauern window, see discussion

by *Froitzheim et al.* [1996]). As depicted in Figure 5, no extension of the Briançonnais into the Eastern Alps is expected. The reconstruction in Figure 8a stipulates an upper plate position of the Briançonnais in respect to the Piemont-Liguria as well as to the Valais Ocean. This minimizes the volume of continental crust underlying the Briançonnais facies domain. However, given the predominance of sinistral strike-slip motion between Europe and the Briançonnais terrane [*Stampfli*, 1993; *Rück*, 1995; *Schmid et al.*, 1990], opening of the Valais Ocean does not necessarily need to be asymmetric.

The proposed paleogeographic situation of the Adula

ALPINE CROSS SECTION ALONG THE NFP-20-EAST TRAVERSE

COMPILED BY S M SCHMID

Molasse basin and Helvetic zone by O.A.Pfiffner, Southern Alps by G.Schoenborn, Geophysics by ETH working group on Deep Seismic Profiling
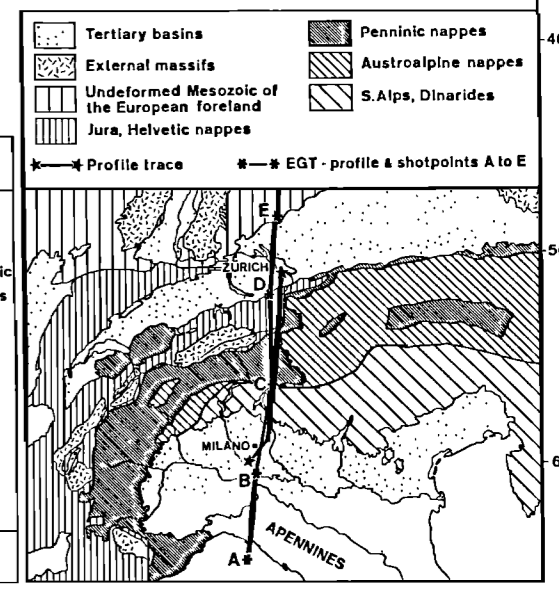
Plate 1. Integrated cross section along an Alpine transect in Eastern Switzerland (see inset for location).
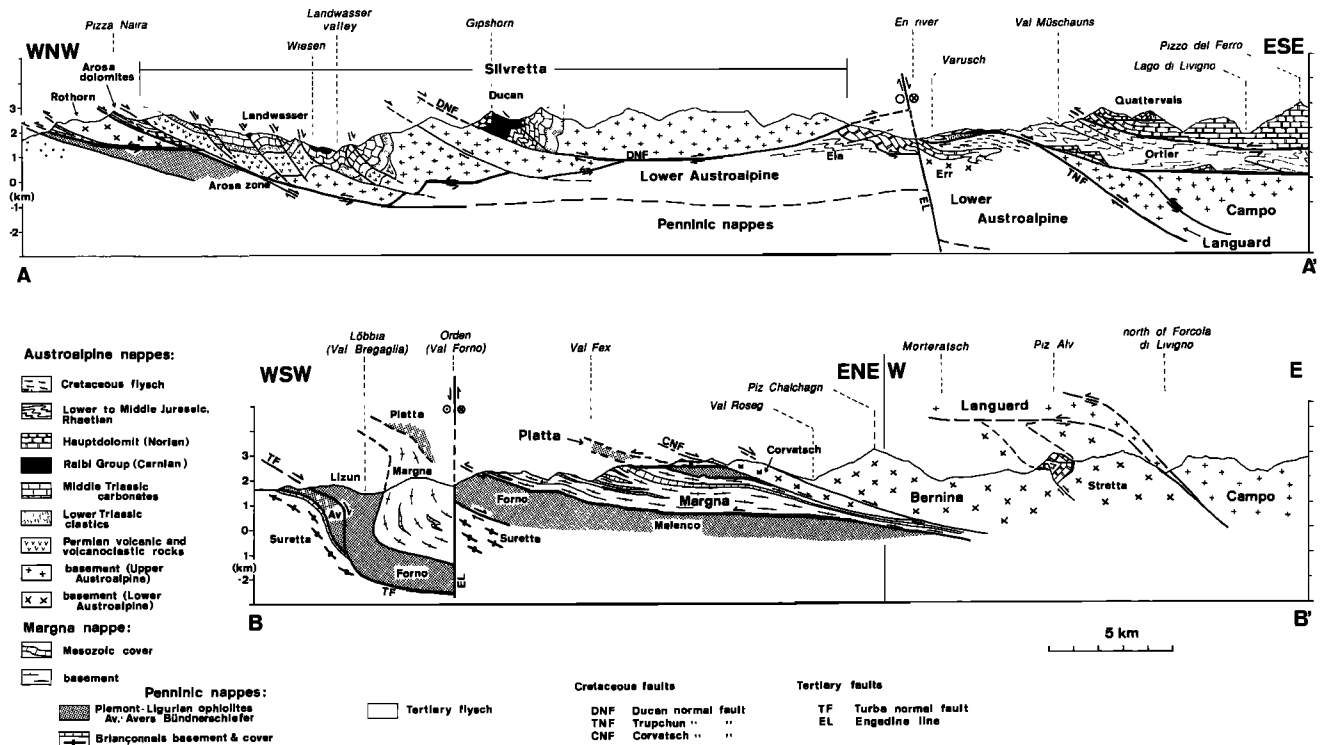
Figure 7. Two tectonic profiles through the Austroalpine nappes in Eastern Switzerland. Profile traces are indicated in Figure 6.

nappe at the distal margin of stable Europe [*Schmid et al.*, 1990, 1996] and north of the Valais ocean has far-reaching consequences regarding the timing of eclogite facies metamorphism in the Adula nappe (a Tertiary rather than Cretaceous age is the corollary), the width of the European distal margin that has been subducted, and the (in this case very high) rates of subduction and subsequent exhumation of the Adula eclogites. In order to minimize amount and rate of Tertiary subduction, a width of only 50 km was assumed for that part of the North Penninic Bündnerschiefer basin that was originally underlain by oceanic crust (Figure 8a).

Cretaceous Orogeny

Figures 6 and 7 illustrate how the Austroalpine nappe pile in eastern Switzerland was assembled by oblique east-over-west imbrication of the NW passive margin of the Apulian microplate [*Froitzheim et al.*, 1994; *Handy et al.*, 1993; *Schmid and Haas*, 1989]. Because the N-S orientation of the profile in Plate 1 is not suited for discussing Cretaceous orogeny, auxiliary WNW-ESE oriented profiles (Figure 7) have been prepared. The associated deformation (Trupchun phase in Figure 4) [*Froitzheim et al.*, 1994] also affected structurally lower units such as the Arosa-Platta ophiolites, the "Ultrapenninic" Margna-Sella nappes and the Lizun-Forno-Malenco ophiolites underlying the Margna nappe [*Ring*

et al., 1988; *Liniger*, 1992; *Spillmann*, 1993]. During Tertiary orogeny a basal thrust displaced all these structurally highest units, which were previously affected by Cretaceous orogeny, to the north by at least 75 km [*Froitzheim et al.*, 1994]. This orogenic lid [*Laubscher*, 1983] overrode the present-day Engadine window and the Prättigau half window (Figure 6) only after Cretaceous orogeny. Sedimentation in the Briançonnais and eastern Valais domains through to the Early Tertiary precludes Cretaceous orogeny within these lower structural units.

We emphasize the existence of two orogenies (Cretaceous and Tertiary) for the following reasons:

1. The kinematics (top to the west to WNW imbrication associated with orogen-parallel strike- slip movements) of Cretaceous orogeny are distinctly different from the top to the north or NNW movements characteristic for Tertiary orogeny.

2. A Late Cretaceous period of extension to be discussed below separates the two orogenies.

3. Subduction associated with eclogite facies metamorphism and subsequent exhumation very probably took place twice in the Alps: first during the Cretaceous and then during the Tertiary (see *Froitzheim et al.* [1996] for an extensive discussion).

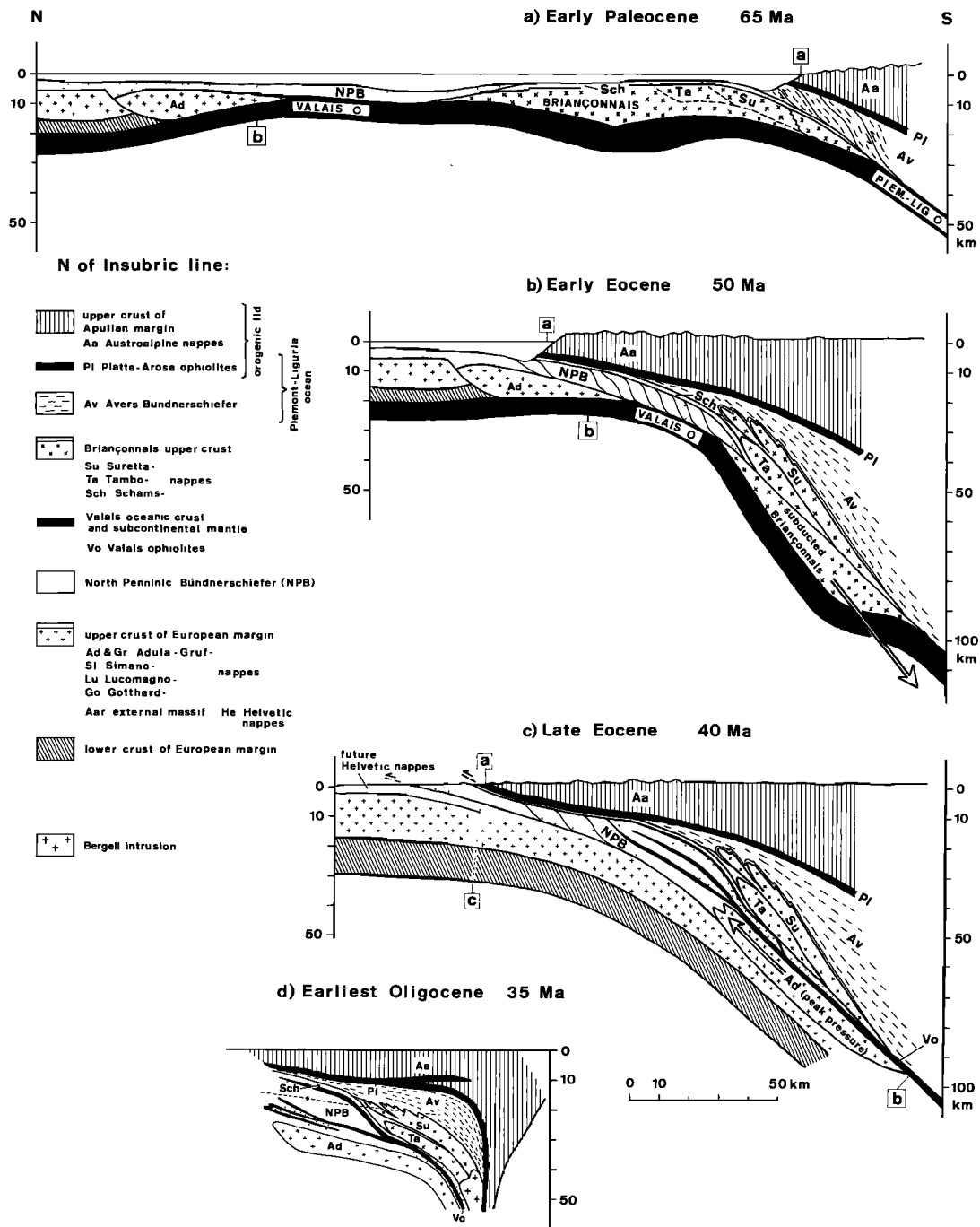Nappe imbrication during the Trupchun phase, the principle phase related to Cretaceous crustal shorten-

Figure 8. Scaled and area-balanced sketches of the kinematic evolution of the eastern Central Alps from (a-b) early Tertiary convergence and subduction to (c) collision and (d-g) postcollisional shortening.

ing, cannot have started before about 90 Ma at the western margin of the Upper Austroalpine nappe system (Ortler unit, Figure 6) because of ongoing pelagic sedimentation (Figure 4) up to the Cenomanian or early Turonian [*Caron et al.*, 1982]. Thrusting further to the east and along the basal thrust of the Oetztal unit

(Figure 6) is constrained to have initiated earlier, at around 100 Ma, by radiometric ages of synkinematic temperature-dominated metamorphism [*Thöni*, 1986; *Schmid and Haas*, 1989]. This westward migration of Cretaceous orogeny is also seen on a much larger scale all across Austria, e.g., from the deposition of synoro-
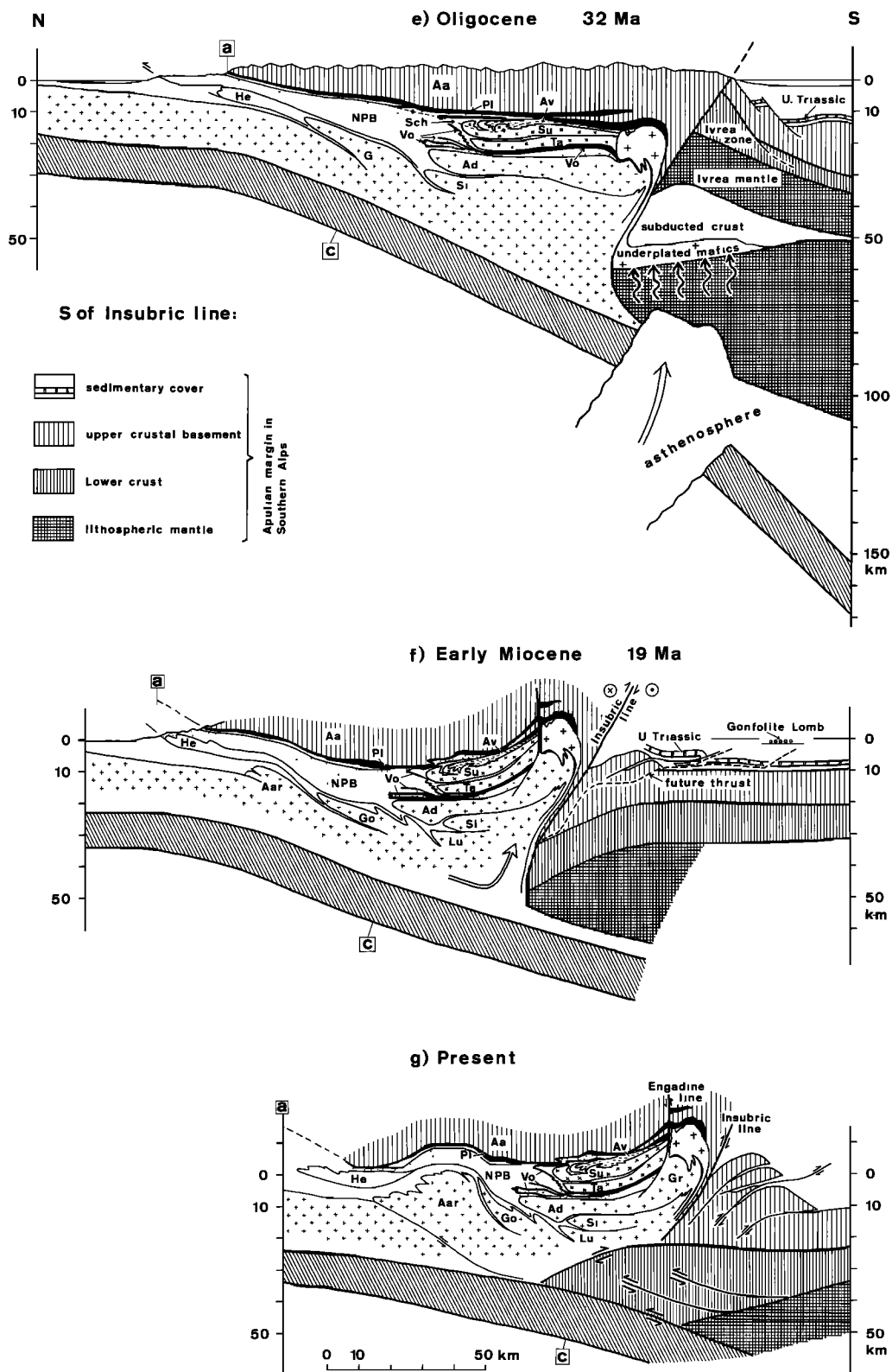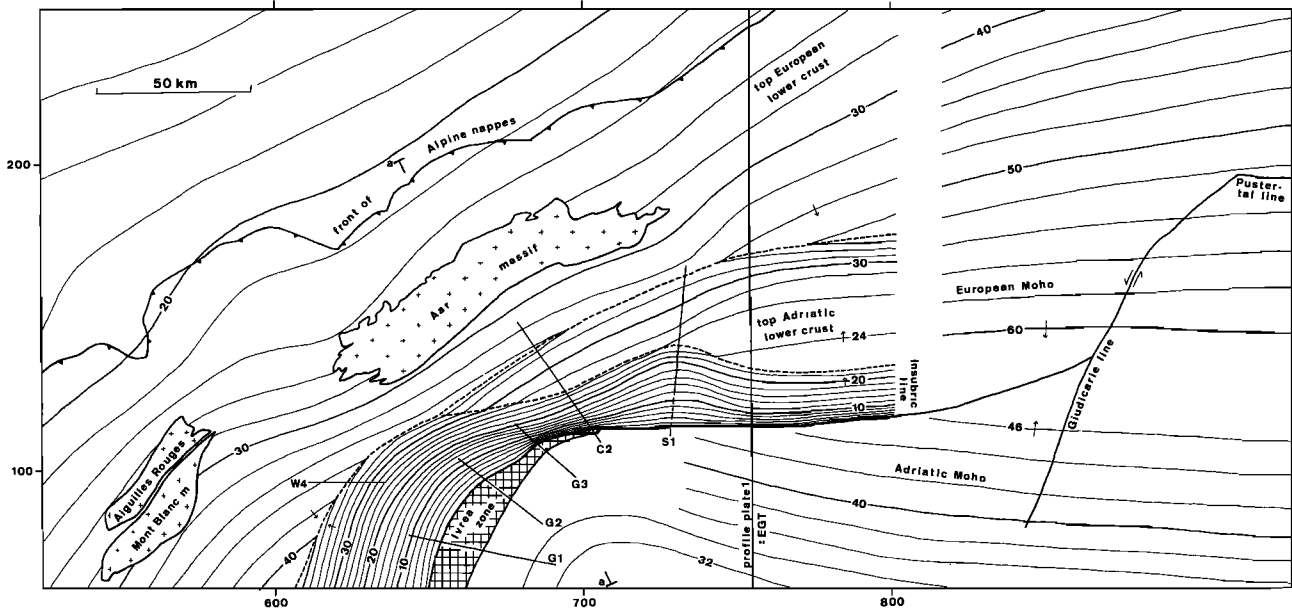
Figure 8. (continued)

Figure 9. Map outlining the contours of the top of the Adriatic lower crustal wedge and its relation to the top of the European lower crust and the Insubric line and, additionally, the Adriatic and European Moho (eastern and southern part of area covered by Figure 9). Contour lines are given in 2 km intervals. The contours of the Insubric line are constrained by field data [*Schmid et al.*, 1987], migrated reflection lines S1 and C2 [*Valasek*, 1992], and 3-D gravity profiles G1, G2 and G3 obtained from 3-D modeling by *Kissling* [1980]. The migrated seismic line W4 is also indicated but was not used for constraining the dip of the Insubric line. Contours of the well-constrained top of the European lower crust and Moho are taken from *Valasek* [1992]. The position of the Adriatic Moho is not well constrained and schematically contoured after data compiled by *Kissling* [1993] and after a seismic refraction profile by *Deichmann et al.* [1986]. Line a-a is the profile trace of Figure 10.

genic chromite-bearing Rossfeldschichten in the early Cretaceous [*Faupl and Tollmann*, 1979] and from the pre-90-Ma age of Alpine eclogite facies metamorphism in the Saualpe [*Thöni and Jagoutz*, 1993]. This supports the postulate that continental collision along the former Meliata-Hallstatt Ocean initiating during the Early Cretaceous in the eastern parts of the Austroalpine units of Austria and the Western Carpathians [*Kozur and Mostler*, 1992] was followed by westward propagation of a thrust wedge into our area of interest by Cenomanian to early Turonian times [*Thöni and Jagoutz*, 1993; *Neubauer*, 1994; *Froitzheim et al.*, 1994].

In Figure 4, Cretaceous orogeny is also shown to have affected the Southern Alps (pre-Adamello phase) [*Brack*, 1981; *Doglioni and Bosellini*, 1987]. The exact timing of this deformation phase is ill-constrained but certainly predates 43 Ma (oldest parts of the Adamello intrusion). Assuming that flysch sedimentation in the Lombardian basin is contemporaneous with this deformation phase and based on radiometric dating of pre-Adamello dykes crosscutting certain thrusts [*Zanchi et al.*, 1990], a Late Cretaceous age is inferred. All the top-south displacements along the Orobic thrust and parts of the displacement along the Coltignone thrust shown

in plate 1 are of pre-Adamello age. This pre-Adamello N-S compression led to more than 25 km shortening.

Activity along a precursor of the Insubric line during or immediately after Cretaceous orogeny is indicated from three lines of evidence:

1. Kinematics and structural style of Cretaceous deformation are totally different within the Austroalpine nappes north of the Insubric line (top-west imbrication, collision, and penetrative deformation associated with metamorphism) and in the Southern Alps (top-south thrusting, foreland deformation).

2. The Insubric line marks the limit between Cretaceous-aged metamorphic units to the north (eclogitic and Barrowian type metamorphism [*Hunziker et al.*, 1989; *Thöni*, 1986; *Thöni and Jagoutz*, 1993]) and the Southern Alps lacking such an overprint. These units must have been at least partially exhumed by or during the Late Cretaceous [*Dal Piaz et al.*, 1972] and juxtaposed with the Southern Alps along this precursor of the Insubric line.

3. The profile of Plate 1 directly shows a fundamental difference between Austroalpine nappes and Southern Alps: The former were emplaced as thin allochthonous flakes onto Penninic ophiolites in Cretaceous times,
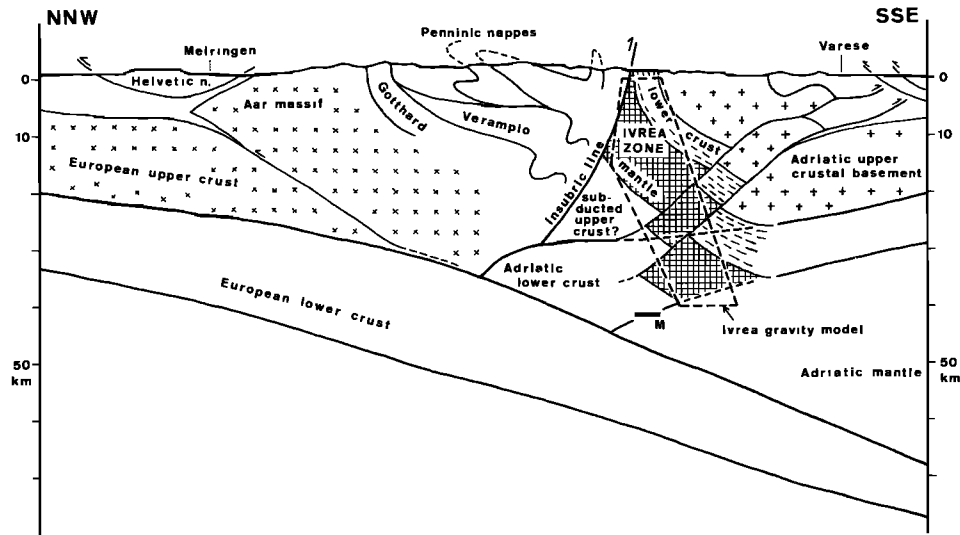
Figure 10. Profile west of the transect of Plate 1 (see Figure 9 for location) constructed using the contours given in Figure 9. The position of the European Moho is taken from *Valasek* [1992]. The Ivrea gravity model corresponds to the model of *Kissling* [1980, profile III]. The top of the Adriatic lower crust is taken from *Valasek* [1992]. The exact position of reflector "M" is unknown; the given approximate position is taken from *Ansorge* [1968].

while the latter remained attached to the lower crust and upper mantle of the Apulian microcontinent.

Late Cretaceous Extension

The westward migrating Cretaceous orogenic wedge underwent severe extension during the Ducan-Ela phase (Figure 4) [*Froitzheim et al.*, 1994], resulting in a series of normal faults at higher tectonic levels (normal faults depicted in Figure 7, such as the Ducan, Trupchun, and Corvatsch normal faults) and folding with horizontal axial planes at a lower tectonic level in the Austroalpine units of eastern Switzerland [*Froitzheim*, 1992; *Froitzheim et al.*, 1994]. Normal faulting disrupts and thins the earlier formed nappe stack and locally leads to omission of nappes, e.g., in the eastern part of section A-A' where the Upper Austroalpine basement (Campo-Languard-Silvretta) is cut out by the Trupchun normal fault (TNF). Extension is also observed further to the east in Austria where it is related to the formation of the Gosau basins [*Ratschbacher et al.*, 1989; *Neubauer*, 1994] between 90 and 60 Ma. In our area of interest this extensional phase is not well dated. We place the Ducan-Ela phase somewhere between 80 Ma (end of the Trupchun phase) and 67 Ma (lower age bracket of a radiometric age determination) [*Tietz et al.*, 1993]. This extensional phase is viewed as being caused by gravitational collapse of an overthickened orogenic wedge in the sense of *Platt* [1986].

Exhumation and cooling of the Austroalpine units during this Ducan-Ela phase have severe implications

for the subsequent orogenic evolution during the Tertiary. The Austroalpine units will largely remain undeformed and will act as a rigid block (orogenic lid) [*Laubscher*, 1983], characterized by friction-controlled Coulomb behavior floating on viscously deforming Penninic units [*Merle and Guillier*, 1989].

Early Tertiary Convergence and Subduction (65-50 Ma)

The tectonic evolution during Tertiary orogeny is summarized in the sketches of Figure 8 (see also the pioneering work along the same transect by *Milnes* [1978, his Figure 3]). The earliest possible onset of thrusting in the units below the Austroalpine nappes and the Platta-Arosa ophiolites (Figures 8a and 8b) is locally constrained by ongoing sedimentation in the Briançonnais domain (Paleocene in the northernmost unit of the Briançonnais, the Falknis nappe) [see *Allemann*, 1957] and in the North Penninic Bündnerschiefer (early Eocene in the Arblatsch and Prättigau flysch) [see *Eiermann*, 1988; *Nänny*, 1948; *Ziegler*, 1956].

The sketch of Figure 8a represents the onset of subduction of the Briançonnais domain due to complete closure of the South Penninic Ocean. The formation of an accretionary wedge within the Avers Bündnerschiefer (Piemont-Liguria Ocean) and northward thrusting of this wedge onto the future Suretta nappe (southernmost Briançonnais domain) is tentatively placed into the early Paleocene (Avers phase, Figure 4). This allows for continued sedimentation within most of the

Table 1. N-S Convergence Derived From the Profiles of Figure 8

Time Interval	Amount of Convergence Across the Alps	Convergence Rate	Plate Tectonic Reconstruction [*Dewey et al.*, 1989]
Early Paleocene to early Eocene (65-50 Ma)	200 km inferred from relative displacement between points a and b in Figure 8. 116 km of thinned continental crust of the Briançonnais domain and the Valais Ocean enter the subduction zone.	1.33 cm yr^{-1}	0.22 cm yr^{-1}, 65 to 55 Ma 0.4 cm yr^{-1}, 55 to 51 Ma
Early to late Eocene (50-40 Ma)	150 km inferred from relative displacement between points a and b in Figure 8. 150 km of distal European margin situated between the southern edge of the Helvetic domain and the southern tip of stable Europe enter the subduction zone.	1.5 cm yr^{-1}	1.2 cm yr^{-1}, 51 to 38 Ma
Late Eocene to Oligocene (40-32 Ma)	45 km inferred from relative displacement between points a and c in Figure 8. Detachment of the Helvetic sediments and deformation within the Subpenninic nappes; unknown amount of shortening in the vicinity of the Insubric line and in the Southern Alps: 45 km represent a minimum estimate only.	at least 0.55 cm yr^{-1}	
Oligocene to early Miocene (32-19 Ma)	a total of 58 km consisting of 33 km from relative displacement between points a and c in Figure 8 (including 6 km out of a total of 21 km shortening in the Aar massif), 15 km from back thrusting along the Insubric line, and 10 km out of a total of 56 km post-Adamello phase shortening in the Southern Alps.	0.45 cm yr^{-1}	0.94 cm yr^{-1}, 38 to 19 Ma
Early Miocene to Recent (19-0 Ma)	a total of 61 km consisting of 15 km from shortening in the Aar massif and 46 km from shortening in the Southern Alps	0.3 cm yr^{-1} (0.5 cm yr^{-1} if deformation stopped at 7 Ma)	0.3 cm yr^{-1}, 19 to 9 Ma 0.43 cm yr^{-1}, 9 to 0 Ma
Total time span (65-0 Ma)	more than 514 km	more than 0.79 cm yr^{-1}	average: 0.72 cm yr^{-1} (amount of convergence, 481 km)

Briançonnais during the Paleocene. Onset of southernmost Briançonnais domain subduction later than 65 Ma would require unrealistically high convergence rates of more than 1.5 cm (see comparison with plate movement velocities shown in Table 1 and discussed later).

By the end of the early Eocene (Figure 8b) the entire width of the Briançonnais domain had been subducted, together with large parts of the North Penninic Bündnerschiefer or Valais basin. Sedimentation in parts of the North Penninic Bündnerschiefer basin continued up to this time [*Etermann*, 1988; *Nänny*, 1948; *Ziegler*, 1956]. The Tambo and Suretta nappes, representing the southern parts of the Briançonnais domain continental basement, reached their peak depth corresponding to the peak pressures of 10-13 kbar [*Baudin and Marquer*, 1993] by this time (about 50 Ma) and were subsequently heated to peak temperatures at 40-35 Ma [*Hurford et al.*, 1989]. Because the onset of penetrative cleavage formation (Ferrera phase of Figure 4) is associated with this metamorphism, it is assumed to have started near the Paleocene-Eocene boundary in

the Tambo and Suretta nappes. This significantly predates the onset of the Ferrera phase deformation in the North Penninic Bündnerschiefer (Figure 4). This interpretation is in accordance with the general trend of northward younging for the onset of penetrative cleavage formation shown in Figure 4. The northern parts of the Briançonnais basement are inferred to have been permanently subducted ("subducted Briançonnais" in Figure 8b). At about 50 Ma, the southern tip of stable Europe, represented by the Adula nappe, is about to enter the subduction zone. Figure 8b represents a snapshot of the onset of final collision caused by the complete closure of the North Penninic Bündnerschiefer realm.

The convergence rate resulting from the relative displacement (200 km) of points "a" (northern edge of the orogenic lid represented by the Austroalpine nappes) and "b" (southern tip of stable Europe, i.e., the Adula nappe) in Figures 8a and 8b is 1.3 cm per year (Table 1). It is noteworthy that the reconstruction of Figure 8 implies that the northern tip of the Austroalpine

nappes marked by "a" in Figure 8a (and corresponding to the front of the Northern Calcareous Alps in a present-day profile, see Figure 8g) has moved northward by a total of some 450 km relative to a point attached to stable Europe presently situated below the northern edge of the Northern Calcareous Alps. This 450 km of convergence (out of a total of 514 km Tertiary N-S convergence across the Alps, Table 1) was accommodated by subduction and shortening within the northern foreland. Relative to stable Europe, point "a" in the sketch of Figure 8a would have to have been located near Pisa in northern Italy at the onset of Tertiary convergence. This illustrates well that Cretaceous orogeny took place far from the present-day position of the Austroalpine nappes at the northern front of the Alps.

Tertiary Collision (50-35 Ma)

Collision of stable Europe with the orogenic lid led to the situation in late Eocene times depicted in Figure 8c, characterized by the subduction of the southern tip of stable Europe (Adula nappe). Eclogite facies overprint in the Adula nappe was immediately followed by rapid exhumation of these eclogites and the establishment of the stack of the higher Penninic nappes by the early Oligocene (Figure 8d).

The amount of convergence between the stages of Figures 8b and 8c (Table 1) is determined by the peak depth of the Adula nappe (corresponding to 27 kbar in the Cima Lunga area) [Heinrich, 1986] and the chosen subduction angle. Other important constraints on the convergence rate are offered by the interpretation of the Adula nappe as representing the southern tip of the European foreland and the Tertiary age of eclogite facies metamorphism in the Adula nappe (Figure 4) [Froitzheim et al., 1996] inferred from geochronological [Becker, 1993; Gebauer et al., 1996] and structural [Partzsch et al., 1994] data. On the basis of these constraints the convergence amounts to 150 km, or 1.5 cm yr^{-1}. The additional 45 km of shortening inferred to have been produced between the stages illustrated in Figures 8c and 8e (indicated by the relative movement of points labeled "a" and "c", see Table 1 and Figure 8) is a minimum estimate because it does not account for an unknown amount of retroshearing associated with the initial phases of back thrusting and vertical extrusion in the vicinity of the Insubric line.

The time span corresponding to the collisional event (50 to 35 Ma) was characterized by penetrative deformation in the Tambo, Suretta, and Schams nappes (Ferrera phase of Figure 4). The Ferrera phase deformation within the North Penninic Bündnerschiefer falls entirely within this time interval. Intense imbrication of Mesozoic sediments, continental basement, and mafic rocks of possibly oceanic origin within the future Adula nappe (Sorreda phase) [Löw, 1987], occurred un-

der prograde conditions. This phase was followed by the Zapport phase [Löw, 1987], which was characterized by extremely penetrative deformation, initially under eclogite facies conditions, followed by lower pressure metamorphic conditions arising from near isothermal decompression.

During Tertiary collision the Penninic nappes thrust north onto the foreland forcing the detachment of sediments that later formed the Helvetic nappes from their original substratum, i.e., the present Gotthard "massif" (D1 in Figure 4) at the end of the collisional stage. The age of the Tertiary cover basal unconformity [Herb, 1988; Lihou, 1995] in the Helvetic nappes and the internal Aar massif (Infrahelvetic units) decreases toward the foreland (Figure 4). This decrease may be interpreted in terms of the northwestward migration of a peripheral bulge within the subducting European plate across the Helvetic realm during the Eocene. During later stages of orogeny this bulge migrated into its present-day location north of the Molasse basin (Black forest). The northward thrusting of the Penninic units also led to a substitution of the cover of the southern Gotthard "massif" by Subpenninic cover slices ("Triassic, Lower, and Middle Jurassic cover slices" in the legend on Plate 1). Northward propagation of the basal Penninic thrust is held responsible for the detachment of North Penninic or Ultrahelvetic (e.g., Sardona flysch) and South Helvetic (e.g., Blattengrat unit) slivers in its footwall. These slivers were dragged over several tens of kilometers and are now found above the Helvetic nappes and, additionally, above the northern Aar massif cover [Trümpy, 1969]. Emplacement of these exotic strip sheets occurred during the Pizol phase (Figure 4) [Milnes and Pfiffner, 1977]. This phase postdates the youngest sediments in the respective footwalls (late Eocene in the Helvetic nappes, early Oligocene in the cover of the Aar massif).

The early phases of exhumation of the Adula nappe brought the frontal parts of this composite unit to more moderate pressures around 6-8 kbar by about 35 Ma (Figure 8d), the onset of temperature-dominated metamorphism (so-called "Lepontine" metamorphism) [Frey et al., 1980] in this particular area (Figure 4). This temperature-dominated metamorphism resulted from decompression along a continuous PT loop [Löw, 1987]. Because the Bergell intrusion is located in direct contact above the Adula nappe (Plate 1) this early phase of exhumation of the Adula nappe must have predated the intrusion. The Bergell tonalite reached the solidus at a depth of merely some 20 km at its base during the early Oligocene according to pressure estimates [Reusser, 1987; Davidson et al., 1996]. Early exhumation of the Adula nappe appears to have been extremely rapid, having occurred over a time span of only 5 m.y. (between the stages represented in Figures 8c and 8d).

Such rapid exhumation by corner flow, extension, or buoyancy forces (see discussion by [Platt, 1993]) is considered unlikely for this early phase of exhumation related to collision. Forced extrusion (recently proposed as a viable alternative model for the exhumation of the Dora Maira eclogites) [Michard et al., 1993] parallel to the subduction shear zone (arrow in Figure 8c) seems to be the most likely mechanism for differential exhumation of the Adula nappe in respect to both higher and lower tectonic units which did not suffer eclogite facies metamorphism.

Slab Detachment, Bergell Intrusion, and Refolding of the Nappe Stack (35-30 Ma)

During the convergence and collision stages discussed above, substantial parts of the more internal Penninic units (oceanic crust, Briançonnais, and distal European continental crust) were subducted. The entire volume of upper crust in the present-day Subpenninic nappes, representing the more proximal parts of the European crust, however, was accreted to the orogenic wedge after Eocene collision. This led to excessive thickening of the orogenic wedge after the Eocene, effectively "clogging" the subduction system, such that only the detached lower crust of the European foreland continued to be subducted from now on.

Figure 8e depicts the result of a first stage of postcollisional shortening described in this section. In this Figure the present-day portion of the Southern Alps along the transect (Plate 1, Figures 8f and 8g) is replaced by a profile across the Ivrea zone [after Zingg et al., 1990] in order to account for about 50 km of dextral strike-slip motion along the Insubric line after early Oligocene times [Fumasoli, 1974; Schmid et al., 1987, 1989]. Also depicted in Figure 8e is slab break-off of the subducting lower parts of the European lithosphere [von Blanckenburg and Davies, 1995; Dal Piaz and Gosso, 1994]. The subduction of light continental lithosphere during collision created extensional forces within the slab, due to opposing buoyancy forces between the deeper subducted, relatively dense lithosphere, and the shallower continental lithosphere [Davies and von Blanckenburg, 1995]. As a result, the slab broke off. This mechanism led to the heating and melting of the overriding lithospheric mantle by the upwelling asthenosphere. Melting probably resulted in mixing of basaltic with assimilated crustal material. Such mixing is indicated by the geochemical and isotopic signatures of the Periadriatic intrusions [von Blanckenburg and Davies, 1995], in particular the Bergell intrusion. Ascent and final emplacement of the Bergell intrusion are related to postcollisional shortening [Rosenberg et al., 1994, 1995; Berger and Gieré, 1995] and are depicted in Figures 8d and 8e.

The 30 and 32 Ma radiometric ages of the Bergell tonalite and granodiorite [von Blanckenburg, 1992] pro-

vide excellent time constraints for dating deformation along the Insubric line and the adjacent Penninic units. Figure 8e depicts the situation immediately after final emplacement of this intrusion at a depth constrained by hornblende barometry [Reusser, 1987; Davidson et al., 1996]. The southern steep belt and the Insubric line must have existed prior to the ascent and final emplacement of the Bergell intrusion [Rosenberg et al., 1995]. Therefore this steep zone is inferred to have formed earlier (Figures 4 and 8d). As also suggested by Trümpy [1992] the ascent of the Bergell pluton is facilitated by movements along the Insubric fault which lead to uplift of the entire southern Penninic zone relative to the Southern Alps between the stages in Figures 8d and 8e.

This differential uplift of the southern Penninic zone was probably caused by upward directed flow in the southern steep belt that was deflected into north directed horizontal movement of the Tambo-Suretta pair (Niemet-Beverin phase of Figure 4, see discussions by Merle and Guillier [1989], Schmid et al. [1990, 1996], and Schreurs [1993, 1995]). This in turn resulted in the spectacular refolding of the Schams nappes and parts of the North Penninic Bündnerschiefer around the hinge of the Niemet-Beverin fold (axial trace indicated in Plate 1 and Figures 8d and 8e).

Movements during this Niemet-Beverin phase were contemporaneous with the closing stages of the Zapport phase in the Adula nappe, the Calanda phase in the Helvetic nappes [Pfiffner, 1986], and the initiation of thrusting along the Glarus thrust (Figure 4). Movement of the trailing edge of the Helvetic nappes at this time, depicted in Figure 8e, ensured that these nappes were not affected by any significant metamorphism (these rocks now exhibit anchizonal conditions). Hence the initial stages of movements in the vicinity of the Insubric line were contemporaneous with north directed transport in the northern foreland. Figure 4 documents that this contemporaneity of "proshears" and "retroshears" in the sense of Beaumont et al. [1994] is maintained during the later stages of post-collisional deformation all through the Neogene.

Intrusion of the Bergell granodiorite at 30 Ma also provides a useful time mark for the end of this earliest stage of postcollisional shortening, the Niemet-Beverin phase (Figure 4) [Schmid et al., 1990]. This phase was associated with E-W extension [Baudin and Marquer, 1993], affecting the Avers Bündnerschiefer, which were cut by an east directed normal fault at the base of the orogenic lid: the Turba normal fault depicted in plate 1 [Nievergelt et al., 1996]. This normal fault is truncated by the Bergell granodiorite, indicating that the Niemet-Beverin phase ended before 30 Ma. Orogen-parallel extension resulted in substantial area reduction of the Avers Bündnerschiefer between the stages of Figures 8d and 8e.

Back Thrusting Along the Insubric Line and Foreland Propagation of the Helvetic Nappes (32 to 19 Ma)

This second step during postcollisional shortening is characterized by back thrusting of the Central Alps over the Southern Alps along a mylonite belt associated with the Insubric line [Schmid et al., 1989]. This back thrusting, in combination with erosion, led to amazingly rapid exhumation of the Bergell area at a rate of 5 mm yr^{-1} [Giger and Hurford, 1989]. Deposition of boulders of Bergell rocks in the Tertiary cover of the Sourthern Alps (mainly in the Como formation, Figure 4) occurred only a few million years after intrusion. Exhumation of the entire Bergell area to a shallow crustal depth must have been completed by about 20 Ma according to the cooling ages from the southern part of the Tambo nappe in the vicinity of this intrusion (cooling below 300°C between 21 and 25 Ma, see Figure 4) (data from Jäger et al. [1967], Purdy and Jäger [1976], and Wagner et al. [1977]).

Effects of the Domleschg and Leis phases [Schmid et al., 1996] which were contemporaneous with back thrusting along the Insubric mylonite belt (Figure 4) were relatively weak within the central Penninic region. The large-scale structure of this region was not substantially altered. However, important contemporaneous movements affect the northern foreland (Figure 4). There the main activity involved movements along the Glarus thrust [Schmid, 1975] and the formation of a penetrative cleavage above and below this thrust (Calanda phase) [Pfiffner, 1986]. The leading edge of the Helvetic nappes emerged at the erosional front of the early Alps in mid-Miocene times (Figure 8f) [Pfiffner, 1985, 1986], as witnessed by Helvetic pebbles in the Upper Freshwater Molasse (OSM). The basal thrust of the Helvetic nappes (Glarus thrust in Plate 1) migrated toward the foreland. Outward migration was also true for the nappe-internal deformation (folds, thrusts, cleavage), which is attributed to the Calanda phase (Figure 4). This phase is of early Oligocene age in the Helvetic nappes [Hunziker et al., 1986] and of mid to late Oligocene age in the internal Aar massif.

Movements at a time near the Oligocene-Miocene boundary led to the situation depicted in Figure 8f. These movements include (1) dextral strike slip under brittle conditions along the Insubric line, without associated back thrusting [Schmid et al., 1989], (2) differential uplift of the Bergell intrusion with respect to the Penninic units, caused by block rotation along the sinistral Engadine line [Schmid and Froitzheim, 1993], (3) E-W orogen-parallel extension at the eastern margin of the Lepontine dome (Forcola phase of Figure 4), and (4) further movement along the Glarus thrust, leading to a second, crenulation cleavage (Ruchi phase in Figure 4) in the area of the internal Aar massif [Pfiffner,

1977; Milnes and Pfiffner, 1977]. Effects of contemporaneous back folding south of the external massifs and in the northern part of the transect (Carassino phase and formation of the Chiera synform in Figure 4) [Löw, 1987] were relatively minor along our transect, but their importance rapidly increases along strike further to the west. There very intense back folding of substantially younger age [Steck and Hunziker, 1994] is observed at the southern margin of the western Aar massif (see Figure 10) [Escher et al., 1988]. The initiation of thrusting in the Molasse basin associated with shortening within the Aar massif (Grindelwald phase in Figure 4) also occurred during this second stage of postcollisional deformation.

Lower Crustal Wedging and Foreland Propagation in the Southern Alps (Post 19 Ma)

Deformation in the southern part of the profile outweighted the one in the northern part during this third stage of postcollisional shortening: 46 km out of a total of 61 km shortening (see Table 1) took place within the Southern Alps after the early Miocene. It is this stage of postcollisional shortening that profoundly influenced the deep structure of the Alps as revealed by geophysical information but which only led to uplift and erosion in the central part of the Alps along our transect.

According to Table 1 the greatest part of post-Adamello shortening in the Southern Alps occurred during this last stage of orogeny. It led to the impressive foreland thrust wedge of the Southern Alps, sealed by the Messinian unconformity that formed at around 7 Ma [Pieri and Groppi, 1981]. This post-Adamello shortening was mainly achieved by thrusting along the Milan thrust and the later out-of-sequence Lecco thrust (Plate 1). According to Schönborn [1992] this N-S-shortening was contemporaneous and related to the displacement of the Periadriatic line by younger movements along the Giudicarie line. Retrodeformation of the post-Adamello shortening leads to a perfect alignment between the Insubric and Pustertal lines (Figure 9) [Schönborn, 1992]. This provides further evidence for postulating a direct relationship between shortening in the Southern Alps and indentation of the Adriatic lower crustal wedge to the north. Indentation of the Adriatic lower crust into the interface between the south dipping European lower crust and the European upper crust (Subpenninic nappes) postdated movements along the Insubric line, as already suggested by Laubscher [1990].

A large part of the shortening within the external Aar massif (Grindelwald phase of Figure 4) and associated thrusting in the Molasse basin were contemporaneous with indentation of the Adriatic lower crustal wedge [Michalski and Soom, 1990]. Outward and downward (in-sequence) propagation of thrusting also affected the

Molasse basin. The depot center of this foredeep (including the Oligocene North Helvetic Flysch deposited on the internal Aar massif) migrated outward at a rate of 0.3 cm yr^{-1} in the Oligocene, slowing down to 0.2 cm yr^{-1} in Miocene times [*Pfiffner*, 1986]. The Grindelwald phase postdates and in Central Switzerland actually deforms the basal thrust of the Helvetic nappes. Within the transect, exhumation of the Aar massif from a paleodepth of approximately 7 km to about 4 km beneath the paleoland surface occurred in the Miocene, as indicated by fission track data [*Michalski and Soom*, 1990]. The thrust indicated in Figure 8g at the base of the Aar massif delimits the boundary between deformed and undeformed European foreland. Updoming of the Aar massif may be viewed as a crustal-scale ramp fold related to a detachment at the interface between lower and upper European crust. This detachment is kinematically linked to the Adriatic lower crustal wedge. The intersection point between proshears and retroshears [*Beaumont et al.*, 1994] is now situated further to the north (i.e., at the northern tip of the lower crustal wedge) and at the interface between lower and upper European crust.

Plate Tectonic Constraints on Tertiary Convergence

Amounts and rates of Tertiary convergence deduced from the kinematic reconstructions of Figure 8 and summarized in Table 1 may be compared to estimates determined by plate reconstructions. The reconstructions in Figure 8 were determined independently of plate tectonic constraints with only one exception: the ill-dated stage represented in Figure 8a was placed in the lower Paleocene in order to avoid convergence rates in excess of 1.5 cm yr^{-1}.

Tertiary convergence is ultimately linked to relative motions between the European and African plates. Although overall convergence rates between these two plates can be estimated (see below), many details of the smaller-scale kinematics are influenced by the motion of smaller blocks such as Iberia, Apulia, Corsica-Sardinia, Mallorca, and Menorca [see *Dewey et al.*, 1989]. In addition, the overall convergence is divided into shortening accommodated in the Mediterranean area and shortening in the Alpine transect studied here. The comparisons made below are thus concerning the order of magnitudes and not the detail.

Europe-Africa plate convergence rates have been analyzed based on the rotation parameters given by *Dewey et al.* [1989]. The plate convergence rates were calculated between a point fixed on the northern end of the eastern transect (Rorschach at +9.5° longitude and 47.5° latitude) and a moving point on Africa (presently located in northern Libya) at the same distance from the rotation pole as Rorschach. Angular velocities for

the various time intervals were determined using an average rotation pole (-15°/31°) determined from the data of *Dewey et al.* [1989]. These velocities were then converted to local velocities (in centimenters per year) and are listed in Table 1. The average velocity over the entire time span (65 Ma to present) is 0.72 cm yr^{-1}, and very close to the estimate of 0.79 cm yr^{-1} determined from our retrodeformation. The total convergence between Europe (Rorschach) and Africa (northern Libya) is 481 km as estimated from the rotation parameters.

Velocities of plate motion suggest much slower convergence rates (0.22-0.4 cm yr^{-1}) in Paleocene times than the estimates based on our reconstruction (1.33 cm yr^{-1}) . The reasons for this discrepancy are not clear but might be due to the independent motions of microcontinents such as the Brianconnais-Iberia terrane [*Stampfli*, 1993]. Plate tectonic convergence rates during Eocene-Oligocene times (0.94 to 1.2 cm yr^{-1}), however, are in excellent agreement with our kinematic reconstruction. Surprisingly good agreement is also reached regarding Miocene to recent times (Table 1).

Discussion

The described Alpine section is similar in many ways to some of the numerical models of crustal-scale deformation provided by *Beaumont et al.* [1994]. The driving force in these models is provided by underthrusting of the underlying mantle lithosphere (in our case European lithosphere), coupled with asymmetric detachment emerging from a velocity discontinuity at a point (point "S") where two inclined step-up shear zones (proshear and retroshear) meet. The gently dipping proshear may easily be compared to the south dipping thrust faults in the Helvetic and northern Penninic zone. More steeply inclined retroshears such as the Insubric line develop above the subduction zone, causing relative uplift of the southern Penninic zone.

The analogy between model 5 of *Beaumont et al.* [1994], characterized by subduction of one third of the crustal column, and the postcollisional stages depicted in Figures 8e-8g is particularly striking. Intracrustal detachment allows for simultaneous foreland migration to the north and south. As illustrated by model M4 [*Beaumont et al.*, 1994], denudation amplifies the movement along the retroshear. Erosion of a thickness of several kilometers of material did in fact occur in late Oligocene times north of the Insubric line [*Giger and Hurford*, 1989]. This resulted in rapid exhumation of high- grade metamorphic rocks north of the Insubric line (Figures 8e and 8f).

In the course of Miocene and Pliocene times the singularity point "S" [*Beaumont et al.*, 1994] between the proshear and retroshear migrated northward (Figures 8f and 8g). This corresponds to the tip of the Adriatic wedge encroaching along the top of the European

lower crust, finally exhuming the Alpine nappe stack. Between 19 Ma (early Miocene, Figure 8f) and 8 Ma (mid Miocene: end of sedimentation in the Molasse basin) the tip of the Adriatic wedge migrated over a distance of about 38 km (related to shortening in the Subalpine molasse and Aar massif), i.e., at a rate of 0.4-0.5 cm yr^{-1}. Miocene thrust loading created the accommodation space [Sinclair and Allen, 1992] in the foredeep, which was then filled with Molasse sediments, i.e., Lower Freshwater Molasse (USM), Upper Marine Molasse (OMM), and Upper Freshwater Molasse (OSM). Migration of the singularity point (tip of the Adriatic wedge) during the Miocene results in exhumation of that part of the orogenic wedge which is located between the proshears and retroshears. During this latest stage the step-up of the proshear includes the basal thrust of the Aar massif. The retroshear comprises the thrust fault at the top of the north moving wedge of Adriatic lower crust, which links to the thrust faults in the Southern Alps (but not the Insubric line, which is inactive by this time).

The model of tectonic evolution depicted in Figure 8 has implications for the rheological properties of the lithosphere, lending strong support to the concept of rheological stratification [e.g., Ord and Hobbs, 1989]. Shallow-dipping upper crustal detachments, typically at depths of around 4-8 km below the top of the basement, are characteristic for nappe formation in the Penninic zone (Figure 8). The depth of these relatively shallow detachment levels possibly coincides with the depth corresponding to the temperatures required for the onset of crystal plasticity in quartz [e.g. Ord and Hobbs, 1989]. As a consequence, substantial parts of European and Briançonnais continental crust were subducted during the stages of early convergence, subduction, and collision according to Figures 8a-8d, in contrast to the findings of Ménard et al. [1991].

During the postcollisional stage the thickness of the European crust increased significantly, as more proximal parts of the European margin (underlying the Helvetic realm) entered the subduction zone. This led to the detachment of the entire upper crust near the interface with the lower crust, apparently a characteristic of postcollisional shortening (Figures 8e-8g). Complete detachment near the top of the highly reflective European lower crust indicates a strength minimum situated immediately above the lower crust. The unchanged thickness of European lower crust all the way from the northern foreland beneath the Adriatic wedge argues for a relatively high strength of this lower crust. This goes against a widespread believe in an inherently weak lower crust [e.g., Meissner, 1989]. Lower crustal rocks whose rheology is largely controlled by that of feldspar and/or mafic minerals may indeed be weak under certain circumstances (see discussion by Rutter and Brodie

[1992]), but no generalizations should be made. Weak lower crust is expected under an elevated geotherm, for example during postorogenic extension leading to the elimination of mountain roots, as was the case at the end of Variscan orogeny [e.g., Eisbacher et al., 1989]. It is this late or post-Variscan event which is generally held responsible for producing the high reflectivity of the European crust, preserved underneath the Alpine orogen. During Alpine orogeny, however, this prestructured lower crust appears to have been subducted without interal deformation due to its high strength to be expected under conditions of a low geotherm (see discussion by Ord and Hobbs [1989]).

Wedging indicates that the Adriatic lower crust also has a relatively high strength in repect to the upper crust, although thickening of this lower crust within this wedge indicates limited deformation by brittle failure and/or crystal plastic flow. Indentation is kinematically related to the contemporaneous formation of a fold and thrust belt confined to upper crustal levels in the Southern Alps. This again demands detachment near the upper interface of the lower crust and, to some extent, also at the lower interface (Moho). It is noteworthy that model M9 of Beaumont et al. [1994], assuming a two-layer rheology for the crust (wet quartz and wet feldspar rheologies) [Jaoul et al., 1984; Shelton and Tullis, 1981], did indeed produce a lower crustal wedge very similar to that shown in Figure 8g.

After having strongly focused on one single cross section through the eastern Central Alps, we need to briefly discuss how representative this section really is for the entire Alps. Figure 9 addresses some of the three-dimensional problems in the Alps in the vicinity of the transect of Plate 1 but does not include the results of a profile provided by the French Etude Continentale et Océanique par Réflexion et Réfraction Sismique and the Italian Consiglio Nazionale delle Ricerche [Nicolas et al., 1990] located outside the area covered by this Figure (ECORS-CROP profile). The contour map of Figure 9 indicates that the Adriatic lower crustal wedge depicted in Plate 1 underthrusts the Insubric line by some 45 km in the east (measured between the intersection point with the north dipping Insubric line and the tip of the wedge). This displacement drops to zero at a point northwest of the Ivrea zone. Hence the Ivrea geophysical body, which is located to the southeast and underneath the NW dipping Insubric line, represents a separate and shallower wedge that reaches the surface in the Ivrea zone. The contours of the Insubric line in Figure 9 have been determined from the profile of Plate 1 and migrated sections of seismic lines S1 and C2 [after Valasek, 1992], from 3-D gravity modeling of the Ivrea body along profiles G1, G2, and G3 [Kissling, 1980, 1982], and from field data [Schmid et al., 1987, 1989].

Westward decreasing amount of wedging of the Adriatic lower crust indicates that the amount of post early Miocene N-S shortening within the Southern Alps (46 km according to Table 1) also decreases toward the west. This points to the existence of a left-lateral transpressive transfer zone running along the western margin of the Southern Alps [Laubscher, 1991] and possibly to some counterclockwise rotation of the Southern Alps. Another left-lateral transpressive zone (the Giudicarie belt) [Laubscher, 1991], extending along the Giudicarie line (Figure 9), delimits the likely eastern termination of the Adriatic wedge. On geometrical grounds this wedge which underthrusts the Central Alps is replaced by the indenter of the eastern Southern Alps which encompasses the entire crustal section situated south of the Tauern window [Ratschbacher et al., 1991]. Note that the Giudicarie line does not appear to offset the contour lines of the European and Adriatic Moho (Figure 9). This means that the Adriatic Moho underlying the lower crustal wedge in the profile of Plate 1 is continuous with the Moho underlying the indenter of the eastern Southern Alps. On both sides of the Giudicarie line the Adriatic Moho overrides the uniformly south dipping European Moho. This confirms the kinematic link between post lower Miocene shortening in the Southern Alps, movements along the Giudicarie line, and north directed indentation of the Adriatic lower crustal wedge underneath the Penninic zone [Laubscher, 1990; Schönborn, 1992].

The 3-D problems associated with the westward termination of the Adriatic lower crustal wedge are far from solved due to incomplete seismic coverage in this area. The profile of Figure 10 represents an attempt to discuss a possible relationship between the Ivrea body and the Adriatic lower crustal wedge. Exhumation of the Ivrea zone [Schmid, 1993] was largely related to Mesozoic passive continental margin formation near the continent-ocean transition (immediately adjacent to the Sesia extensional allochthon indicated in Figure 5). Alpine orogeny steepened the entire crustal section into its present-day subvertical orientation (Figure 10) [Zingg et al., 1990], thereby probably exposing a segment of the ancient Moho of the Adriatic crust at the surface. This led some authors [e.g., Giese and Buness, 1992] to postulate a dramatic change in the present-day topography of the Adriatic Moho near the western termination of the Ivrea zone; the northward dip of the Moho along the profile of Plate 1 is postulated to change into a southeasterly dip, away from the Ivrea zone.

This direct correlation of the paleo-Moho exposed in the Ivrea zone with the present-day Moho beneath the Southern Alps is at odds with seismic refraction data obtained along a refraction profile parallel to the Ivrea zone [Ansorge, 1968]. These seismic data, together with

3-D gravity modeling by Kissling [1980, 1982] point to the existence of a velocity and density inversion underneath the Ivrea body and a second Adriatic Moho (labeled "M" in Figure 10). This second (present-day) Moho may be continuous with the north dipping Adriatic Moho (Plate 1) east of Figure 10. The cause of the density inversion below the Ivrea zone is controversial. Schmid et al. [1987] speculated that it may be due to Cretaceous-age subduction of parts of the Sesia zone below the Ivrea body. Figure 10 shows that the lower crustal wedge of our transect (Plate 1) is not identical with the Ivrea geophysical body and that the Ivrea zone has been underthrust by this wedge which occupies a deeper structural level. However, the exact geometry of the underthrust material and associated overthrust blocks within this part of the Southern Alps is unknown and only drawn schematically in Figure 10.

The southern extension of the Ivrea geophysical body was encountered along the ECORS-CROP profile of the Western Alps [Nicolas et al., 1990] whose trace is situated southwest of the area covered by Figure 9. From a purely geometrical point of view this profile, also characterized by wedging, exhibits similarities with the transect of the Swiss-Italian Alps. In the case of the ECORS- CROP profile, however, wedging involves large slabs of mantle material according to gravity modeling [Rey et al., 1990]. Also, as previously discussed with the help of Figure 9, the lower crustal wedge of Plate 1 does find its western termination near the Canavese line and cannot be directly connected with the mantle wedge encountered along the ECORS-CROP profile. As discussed by Nicolas et al. [1990], it is not clear if these slabs formed by rupture of the entire European lithosphere, or alternatively, by wedging of an Adriatic mantle slice which represents the western extension of the Ivrea geophysical body at a depth of 25-30 km [Roure et al., 1990]. According to Roure et al. [1990] this wedging must have occurred prior to the deposition of Neogene deposits in the western Po plain. Hence wedging in the ECORS-CROP profile is contemporaneous with back thrusting along the Insubric line (Oligocene) and predates wedging in the transect across the Swiss-Italian Alps during the Miocene.

Reconciliation of our estimate of some 500 km of N-S shortening along the profile of Plate 1 since the Paleocene with the smaller amounts of E-W shortening recorded in the Western Alps [e.g., Nicolas et al., 1990] remains a major problem, providing a challenge for future investigations. Laubscher [1991] pointed out that large amounts of strike-slip faulting and independent motions of large blocks such as the Adriatic block are inevitable. The large amount of N-S convergence postulated along the eastern Swiss traverse (Plate 1) indicates that much of the E-W shortening in the Western Alps must be due to an independent westward motion

of the Adriatic block during the Neogene and decoupled from the Central Alps by dextral movements along the Insubric line and its precursors. Deflection of a unique west-northwest directed plate movement vector of the Adriatic block (part of the Apulian microplate) into north and west directed components of tectonic transport (in the Western and Central Alps, respectively) due to gravitational forces [*Platt et al.*, 1989] can hardly lead to the very substantial amount of N-S convergence deduced in this study.

References

Allemann, F, Geologie des Fürstentums Liechtenstein (Südwestlicher Teil) unter besonderer Berücksichtigung des Flyschproblems, *Jahrb. Hist. Ver. Liechtenstein, 56*, 1-244, 1957

Allemann, F, and B. Schwizer, Zur Geologie der Rheintalseite im Fürstentum Liechtenstein (Exkursion D am 19. April 1979), *Jahresber. Mitt. Oberrheinischen Geol. Ver., 61*, 67-77, 1979.

Ansorge, J., Die Struktur der Erdkruste an der Westflanke der Zone von Ivrea, *Schweiz. Mineral. Petrogr. Mitt., 48*, 247-254, 1968

Argand, E., Sur l'arc des Alpes Occidentales, *Eclogae Geol. Helv., 14*, 145-204, 1916.

Baudin, T, and D. Marquer, Metamorphisme et deformation dans la nappe de Tambo (Alpes Centrales Suisses) Evolution de la substitution phengitique au cours de la deformation alpine, *Schweiz Mineral. Petrogr. Mitt., 73*, 285-300, 1993

Baumann, M, Three-dimensional modeling of the crust-mantle boundary in the Alpine region, Ph.D thesis, Eidg. Tech. Hochsch., Zürich, Switzerland, 1994.

Beaumont, C., P H Fullsack, and J. Hamilton, Styles of crustal deformation in compressional orogens caused by subduction of the underlying lithosphere, *Tectonophysics, 232*, 119-132, 1994

Becker, H, Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine dome (Swiss Alps). New evidence for Eocene high-pressure metamorphism in the central Alps, *Geology, 21*, 599-602, 1993

Berger, A., and R. Gieré, Structural observations at the eastern contact of the Bergell Pluton, *Schweiz. Mineral. Petrogr. Mitt., 75*, 241-258, 1995.

Berger, A, C Rosenberg, and S M. Schmid, Ascent, emplacement and exhumation of the Bergell Pluton within the Southern Steep Belt of the Central Alps, *Schweiz. Mineral. Petrogr. Mitt.*, in press, 1996.

Bernoulli D., P. Heitzmann, and A Zingg, Central and southern Alps in southern Switzerland: Tectonic evolution and first results of reflection seismics, in *Deep Structure of the Alps*, edited by F Roure et al, *Mém. Soc. Géol. Fr., 156*, 289-302, 1990

Bernoulli, D., G. Bertotti, and N Froitzheim, Mesozoic faults and associated sediments in the Austroalpine-South Alpine passive continental margin, *Mem. Soc. Geol. Ital., 45*(1990), 25-38, 1993

Bertotti, G., Early Mesozoic extension and Alpine shortening in the western Southern Alps: The geology of the area between Lugano and Menaggio (Lombardy, Northern Italy), *Mem. Sci. Geol., 43*, 17-123, 1991.

Bertotti, G., V. Picotti, D Bernoulli, and A Castellarin, From rifting to drifting Tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous, *Sediment. Geol., 86*, 53-76, 1993.

Brack, P., Structures in the southwestern border of the Adamello intrusion (Alpi bresciane, Italy), *Schweiz. Mineral. Petrogr. Mitt., 61*, 37-50, 1981.

Bucher-Nurminen, K, and G. Droop, The metamorphic evolution of garnet-cordierite- sillimanite gneisses in the Gruf Complex, *Contrib. Mineral. Petrol., 84*, 215-227, 1983.

Buness, H., Krustale Kollisionsstrukturen an den Rändern der nordwestlichen Adriaplatte, Ph.D. thesis, Freie Universität, Berlin, Germany, 1992.

Burkhard, M., Aspects of the large-scale Miocene deformation in the most external part of the Swiss Alps (Subalpine Molasse to Jura fold belt), *Eclogae Geol. Helv., 83*, 559-583, 1990.

Caron, M., R. Dössegger, R. Steiger, and R. Trümpy, Das Alter der jüngsten Sedimente der Ortler-Decke (Oberostalpin) in der Val Trupchun (Schweizerischer Nationalpark, Graubünden), *Eclogae Geol. Helv., 75*, 159-169, 1982.

Cernobori, L., and R. Nicolich, Seismic profiles in the Central Alps, in *Proceedings of Symposium "CROP-Alpi Centrali"*, edited by A. Montrasio and E. Sciesa, *Quad. Geodinamica Alpina Quat., 2*, 65-77, 1994.

Conti, P., G. Manatschal, and M. Pfister, Synrift sedimentation, Jurassic and Alpine tectonics in the central Ortler nappe (Eastern Alps, Italy), *Eclogae Geol. Helv., 87*, 63-90, 1994.

Dal Piaz, G.V., and G. Gosso, Some remarks on evolution of the Alpine lithosphere, in *Proceedings of Symposium "CROP-Alpi Centrali"*, edited by A. Montrasio and E. Sciesa, *Quad. Geodinamica Alpina Quat., 2*, 93-101, 1994.

Dal Piaz, G.V., J.C. Hunziker, and G. Martinotti, La zona Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi nordoccidentali interne, *Mem. Soc. Geol. Ital., 11*, 433-466, 1972.

Davidson, C., C. Rosenberg, and S.M. Schmid, Synmagmatic folding of the base of the Bergell pluton, Central Alps, *Tectonophysics*, in press, 1996

Davies, J.H., and F. von Blanckenburg, Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens, *Earth Planet. Sci. Lett., 129*, 85-102, 1995.

Deichmann, N., J. Ansorge, and S. Mueller, Crustal structure of the Southern Alps beneath the intersection with the European geotraverse, *Tectonophysics, 126*, 57-83, 1986.

Dercourt, J., et al. (18 authors), Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias, *Tectonophysics, 123*, 241-315, 1986.

Dewey, J.F., M L. Helman, E. Turco, D.H.W. Hutton, and S.D. Knott, Kinematics of the western Mediterranean, in *Alpine Tectonics*, edited by M.P. Coward, D. Dietrich, and R.G. Park, *Geol. Soc. Spec. Publ. London, 45*, 265-283, 1989.

Diethelm, K.H., Petrographische und geochemische Untersuchungen an basischen Gesteinen der Bergeller Intrusion, Ph.D. thesis, Eidg. Tech. Hochsch., Zürich, Switzerland, 1989.

Doglioni, C., and A. Bosellini, Eoalpine and mesoalpine tectonics in the Southern Alps, *Geol. Rundsch., 76*, 735-754, 1987.

Droop, G.T, and K. Bucher-Nurminen, Reaction textures and metamorphic evolution of sapphirine- bearing granulites from the Gruf Complex, Italian Central Alps, *J. Petrol., 25*, 766-803, 1984.

Eiermann, D., Zur Stellung des Martegnas-Zuges, *Eclogae Geol. Helv., 81*, 259-272, 1988

Eisbacher, G.H., E. Lüschen, and F Wickert, Crustal-scale thrusting and extension in the Hercynian Schwarzwald and Vosges, central Europe, *Tectonics, 8*, 1-21, 1989.

Escher, A, H Masson, and A. Steck, Coupes géologiques des Alpes occidentales suisses, *Mém. Géol. Lausanne, 2*, 1988

Etter, U, Stratigraphische und strukturgeologische Untersuchungen im Gotthardmassivischen Mesozoikum zwischen dem Lukmanierpass und der Gegend von Ilanz, Ph D. thesis, Univ of Bern, Bern, Switzerland, 1987

Faupl, P, and A. Tollmann, Die Rossfeldschichten Ein Beispiel für Sedimentation im Bereich einer tektonisch aktiven Tiefseerinne aus der kalkalpinen Unterkreide, *Geol. Rundsch., 68*, 93-120, 1979.

Florineth, D, and N. Froitzheim, Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubünden, Switzerland) Evidence for Early Cretaceous opening of the Valais ocean, *Schweiz. Mineral. Petrogr. Mitt., 74*, 437-448, 1994.

Frey, M., K. Bucher, E. Frank, and J Mullis, Alpine metamorphism along the Geotra-

verse Basel-Chiasso - A review, *Eclogae Geol. Helv.*, *73*, 527-546, 1980.

Frisch, W , Tectonic progradation and plate tectonic evolution of the Alps, *Tectonophysics*, *60*, 121- 139, 1979.

Froitzheim, N , Formation of recumbent folds during synorogenic crustal extension (Austroalpine nappes, Switzerland), *Geology*, *20*, 923-926, 1992

Froitzheim, N., and G P Eberli, Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland, *Geol. Soc. Am. Bull.*, *102*, 1297-1308, 1990.

Froitzheim, N , and G. Manatschal, Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (Eastern Switzerland), *Geol. Soc. Am. Bull.*, in press, 1996.

Froitzheim, N., S M. Schmid, and P Conti, Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden, *Eclogae Geol. Helv.*, *87*, 559-621, 1994

Froitzheim, N , S.M. Schmid, and M. Frey, Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps A working hypothesis, *Eclogae Geol. Helv.*, in press, 1996.

Fumasoli, M , Geologie des Gebietes nördlich und sudlich der Jorio-Tonale-Linie im Westen von Gravedona, Mitt Geol. Inst Eidg. Tech. Hochsch Univ Zürich, 194, 1-230, 1974

Gebauer, D , A P-T-t path for (Ultra?-) high-pressure ultramafic/mafic rock associations and their felsic country rocks based on SHRIMP-dating of magmatic and metamorphic zircon domains Example Alpi Arami (Central Swiss Alps), in *Earth Processes: Reading the Isotopic Code, Geophys. Monogr Ser.*, vol. 95, edited by A Basu and S R Hart, pp. 307-328, AGU, Washington, D C , in press, 1996.

Giese, P , and H. Buness, Moho depth, in *Atlas of Compiled Data - A Continent Revealed - The European Geotraverse*, edited by R Freeman and St Mueller, pp 11-13, Cambridge Univ. Press, New York, 1992

Giger, M., and A J Hurford, Tertiary intrusives of the Central Alps Their Tertiary uplift, erosion, redeposition and burial in the South-Alpine foreland, *Eclogae Geol. Helv.*, *82*, 857-866, 1989

Hafner, M , Strukturgeologische und geochemische Untersuchungen von leukokraten Granitgängen und Migmatiten der südlichen Adula am Monte Peschiera (It), diploma thesis, Univ of Basel, Basel, Switzerland, 1994

Handy, M , M Herwegh, and R. Regli, Tektonische Entwicklung der westlichen Zone von Samedan (Oberhalbstein, Graubunden, Schweiz), *Eclogae Geol. Helv.*, *86*, 785-817, 1993

Harland, W B , A.V Armstrong, L E Cox, A G Craig, and D G Smith, *A Geologic Time Scale 1989*, 265 pp , Cambridge Univ Press, New York, 1989

Heinrich, C A , Eclogite facies regional metamorphism of hydrous mafic rocks in the Central Alpine Adula nappe, *J. Petrol.*, *27*, 123-154, 1986

Heitzmann, P., Zur Metamorphose und Tektonik im südöstlichen Teil der Lepontischen Alpen, *Mineral.. Petrogr. Mitt.*, *55*, 467-522, 1975.

Herb, R , Eocäne Palaogeographie und Palaotektonik des Helvetikums, *Eclogae Geol. Helv.*, *83*, 611- 657, 1988

Hitz, L., and O.A. Pfiffner, A 3-D crustal model of the eastern external Aar massif interpreted from a network of deep seismic profiles, *Schweiz. Mineral. Petrogr. Mitt.*, *74*, 405-420, 1994

Holliger, K , Ray-based image reconstruction in controlled-source seismology with an application to seismic reflection and refraction data in the Central Swiss Alps, Ph.D. thesis, 156 pp., Eidg Tech Hochsch., Zürich, Switzerland, 1991

Holliger, K., and E Kissling, Ray theoretical depth migration: Methodology and application to deep seismic reflection data across the eastern and southern Swiss Alps, *Eclogae Geol. Helv.*, *84*, 369-402, 1991.

Holliger K , and E Kissling, Gravity interpretation of a unified 2-D acoustic image of the central Alpine collision zone, *Geophys. J. Int , 111*, 213-225, 1992

Hunziker, J , M Frey, N Clauer, R D Dallmeyer, H. Friedrichsen, W Flehmig, K Hochstrasser, P. Roggwiler, and H Schwander, The evolution of illite to muscovite Mineralogical and isotopic data from the Glarus Alps, Switzerland, *Contrib. Mineral. Petrol.*, *92*, 157-180, 1986

Hunziker, J C , J Desmons, and G. Martinotti, Alpine thermal evolution in the central and the western Alps, in *Alpine Tectonics*, edited by M. Coward, D Dietrich, and R Park, *Geol. Soc. Spec. Publ. London, 45*, 353-367, 1989

Hurford, A J , M. Flysch, and E. Jäger, Unraveling the thermo-tectonic evolution of the Alps A contribution from fission track analysis and mica dating, in *Alpine Tectonics*, edited by M.Coward, D Dietrich, and R G Park, *Geol. Soc. Spec. Publ. London, 45*, 369-398, 1989.

Jäger, E., E. Niggli, and E. Wenk, Rb-Sr Altersbestimmungen an Glimmern der Zentralapen, *Beitr. Geol. Karte Schweiz, 134*, 1-67, 1967.

Jaoul, O., J. Tullis, and A.K. Kronenberg, The effect of varying water contents on the creep behaviour of Heavitree quartzite, *J. Geophys. Res.*, *89*, 4298-4312, 1984.

Kissling, E., Krustenaufbau und Isostasie in der Schweiz, Ph.D. thesis, Eidg. Tech. Hochsch., Zürich, Switzerland, 1980.

Kissling, E., Aufbau der Kruste und des oberen Mantels in der Schweiz, *Geodätisch-Geophys. Arb. Schweiz Schweiz. Geodätische Komm., 35*, 37-126, 1982.

Kissling, E., Deep structure of the Alps - What do we really know?, *Phys. Earth Planet. Inter.*, *79*, 87-112, 1993.

Kozur, H., The evolution of the Meliata-Hallstatt ocean and its significance for the early evolution of the Eastern Alps and Western Carpathians, *Palaeogr. Palaeoclimatol. Palaeoecol.*, *87*, 109-135, 1992.

Kozur, H., and H. Mostler, Erster Paläontologischer Nachweis von Meliaticum und Süd-Rudabanyaicum in den nördlichen Kalkalpen (Oesterreich) und ihre Beziehungen zu den Abfolgen in den Westkarpaten, *Geol. Paläontol. Mitt. Innsbruck, 18*, 87-129, 1992.

Laubscher, H. P., Detachment, shear, and compression in the central Alps, *Mem. Geol. Soc. Am.*, *158*, 191-211, 1983.

Laubscher, H. P., Material balance in Alpine orogeny, *Geol. Soc. Am Bull.*, *100*, 1313-1328, 1988.

Laubscher, H.P., Deep seismic data from the central Alps: Mass distributions and their kinematics, in *Deep Structure of the Alps*, edited by F Roure et al., *Mém. Soc. Géol. Fr.*, *156*, 335-343, 1990.

Laubscher, H. P., The arc of the Western Alps today, *Eclogae Geol. Helv.*, *84*, 631-659, 1991.

Laubscher, H.P., Deep structure of the Central Alps in the light of recent seismic data, *Geol. Rundsch.*, *83*, 237-248, 1994.

Lein, R., Evolution of the Northern Calcareous Alps during Triassic times, in *Geodynamics of the Eastern Alps*, edited by W. Flügel and P. Faupl, pp. 85-102, Deuticke, Vienna, 1987.

Lemoine, M., P Tricart, and G. Boillot, Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): In search of a genetic model, *Geology, 15*, 622-625, 1987

Lihou, J.C., A new look at the Blattengrat unit of eastern Switzerland: Early Tertiary foreland basin sediments from the South Helvetic realm, *Eclogae Geol. Helv.*, *88*, 91-114, 1995.

Liniger, M., Der ostalpin-penninische Grenzbereich im Gebiet der nördlichen Margna-Decke (Graubünden, Schweiz), Ph.D. thesis, Eidg. Tech Hochsch., Zürich, Switzerland, 1992.

Litak, R.K., R.H. Marchant, O A. Pfiffner, L.D. Brown, S. Sellami, L. Levato, J.-J. Wagner, and R. Olivier, Crustal structure and reflectivity of the Swiss Alps from three-dimensional seismic modelling, 2, Penninic nappes, *Tectonics, 12*, 925-935, 1993

Löw, S., *Die tektono-metamorphe Entwicklung der nördlichen Adula-Decke, Beitr. Geol. Karte Schweiz, 161*, 84 pp , 1987

Marchant, R , *The underground of the Western Alps, Mém. Géol. Lausanne, 15*, 137 pp , 1993

Marson, I , L. Orlando, and M.Stoka, Gravity model on the CROP Profile, in *Proceedings of Symposium "CROP-Alpi Centrali"*, edited by A Montrasio and E. Sciesa, *Quad. Geodinamica Alpina Quat., 2*, 161-169, 1994

Meissner, R , Rupture, creep, lamellae and crocodiles· Happenings in the continental crust, *Terra Nova, 1*, 17-28, 1989.

Ménard, G , P. Molnar, and J. Platt, Budget of crustal shortening and subduction of continental crust in the Alps, *Tectonics, 10*, 231-244, 1991

Merle, O and B Guillier, The building of the Central Swiss Alps: An experimental approach, *Tectonophysics, 165*, 41-56, 1989

Michalski, I , and M Soom, The Alpine thermo-tectonic evolution of the Aar and Gotthard massifs, Central Switzerland: Fission track ages on zircon and apatite and K-Ar mica ages, *Schweiz. Mineral. Petrogr. Mitt., 70*, 373-387, 1990

Michard, A , C Chopin, and C Henry, Compression versus extension in the exhumation of the Dora-Maira coesite-bearing unit, Western Alps, Italy, *Tectonophysics, 221*, 173-193, 1993

Milano, F P , G Pennacchioni, and I.M. Spalla, Alpine and pre-Alpine tectonics in the central Orobic Alps (Southern Alps), *Eclogae Geol. Helv., 81*, 273-294, 1991.

Milnes, A G , Structure of the Pennine zone (Central Alps). a new working hypothesis, *Geol. Soc. Am. Bull., 85*, 1727-1732, 1974.

Milnes, A.G., Structural zones and continental collision, Central Alps, *Tectonophysics, 47*, 369-392, 1978.

Milnes, A.G., and O A Pfiffner, Structural development of the Infrahelvetic complex, eastern Switzerland, *Eclogae Geol. Helv., 70*, 83-95, 1977

Montrasio, A., R Bersezio, F Forcella, F. Jadoul, and E Sciesa, Geological interpre-

tation of the profile CROP - Central Alps (Passo Spluga - Bergamo), *Quad. Geodinamica Alpina Quat.*, *2*, 171-186, 1994

Mueller, S , A new model of the continental crust, in *The Earth's Crust. Its Nature and Physical Properties, Geophys Monogr. Ser.*, vol 20, edited by J.G. Heacock, pp. 289-317, AGU, Washington, D C., 1977

Mueller, S , J Ansorge, R Egloff, and E. Kissling, A crustal cross section along the Swiss Geotraverse from Rhinegraben to the Po Plain, *Eclogae Geol. Helv.*, *71*, 19-33, 1980

Nanny, P., Zur Geologie der Prättigauschiefer zwischen Rhätikon und Plessur, Ph.D. thesis, Univ. of Zürich, Zürich, Switzerland, 1948

Neubauer, F , Kontinentkollision in den Ostalpen, *Geowissenschaften*, *12*, 136-140, 1994.

Nicolas, A , R Polino A Hirn, R Nicholic, and ECORS-CROP WORKING GROUP, ECORS-CROP traverse and deep structure of the western Alps A synthesis, in *Deep Structure of the Alps*, edited by F. Roure et al , *Mém. Soc. Géol. Fr.*, *156*, 15-27, 1990.

Nievergelt, P., M. Liniger, N Froitzheim, and R Ferreiro Mählmann, Early to mid Tertiary extension in the Central Alps. The Turba mylonite zone, Eastern Switzerland, *Tectonics*, in press, 1996.

Ord, A., and B E. Hobbs, The strength of the continental crust, detachment zones and the development of plastic instabilities, *Tectonophysics*, *158*, 269-289, 1989

Partzsch, J.H., M. Frey, P Kruspan, C Meyre, and S.M. Schmid, Die tektonometamorphe Entwicklung der mittleren Adula-Decke (Zentralalpen, Schweiz), in *Extended abstracts, 5 Symposium TSK, Göttingen, Göttinger Arb Geol. Paläontol., Sb.1*, 124-126, 1994

Pfiffner, O A., Tektonische Untersuchungen im Infrahelvetikum der Ostschweiz, *Mitt. Geol. Inst. Eidg. Tech. Hochsch. Univ. Zürich*, *217*, 1-432, 1977

Pfiffner, O A , Fold-and-thrust tectonics in the Helvetic nappes (E Switzerland), in *Thrust and Nappe Tectonics*, edited by K R. Mc Clay and N.J. Price, *Spec. Publ Geol. Soc. London*, *9*, 319-327, 1981

Pfiffner, O.A , Displacements along thrust faults, *Eclogae Geol. Helv.*, *78*, 313-333, 1985.

Pfiffner, A., Evolution of the north Alpine foreland basin in the Central Alps, *Spec. Publ. Int. Assoc. Sedimentol.*, *8*, 219-228, 1986.

Pfiffner, O.A., Alpine orogeny, in *A Continent Revealed: The European Geotraverse*, edited by D. Blundell, R Freeman, and S. Müller, pp. 180-190, Cambridge Univ Press, New York, 1992

Pfiffner, O A , E Klaper, A M Mayerat, and P Heitzmann, Structure of the basement-cover contact in the Swiss Alps, in *Deep Structure of the Alps*, edited by F Roure et al., *Mém. Soc. Géol. Fr.*, *156*, 247-262, 1990a

Pfiffner, O.A , W. Frei, P Valasek, M Stäuble, L. Levato, L Dubois, S M Schmid, and S B. Smithson, Crustal shortening in the Alpine orogen Results from deep seismic reflection profiling in the Eastern Swiss Alps, line NFP 20-East, *Tectonics*, 9, 1327-1355, 1990b.

Pieri, M., and G. Groppi, Subsurface geological structure of the Po Plain, Italy, *Pubbl. 414*, pp. 1-37, Progetto Finalizzato Geodinamica, Cons Naz della Ric., Bologna, Italy, 1981.

Platt, J P., Dynamics of orogenic wedges and the uplift of high pressure metamorphic rocks, *Geol Soc. Am. Bull.*, *97*, 1037-1053, 1986

Platt, J P , Exhumation of high-pressure rocks· A review of concepts and processes, *Terra Nova*, *5*, 119-133, 1993.

Platt, J.P., J H. Behrmann, P.C Cunningham, J F Dewey, M. Helman, M Parish, M.G. Shepley, S Wallis, and P.J. Weston, Kinematics of the Alpine arc and the motion history of Adria, *Nature*, *337*, 158-161, 1989

Polino, R., G V Dal Piaz, and G Gosso, Tectonic erosion of the Adria margin and accretionary processes for the Cretaceous orogeny in the Alps, in *Deep Structure of the Alps*, edited by F Roure et al , *Mém. Soc. Géol. Fr.*, *156*, 345-367, 1990

Probst, P., *Die Bündnerschiefer des nördlichen Penninikums zwischen Valser Tal und Passo di San Giacomo, Beitr. Geol. Karte Schweiz*, *153*, 1980

Purdy, J W., and E Jäger, *K-Ar ages on rock-forming minerals from the Central Alps, Mem. Ist. Geol. Mineral. Univ Padova*, *30*, 1976.

Ratschbacher, L., F Neubauer, S M. Schmid, and J Neugebauer, Extension in compressional orogenic belts. The Eastern Alps, *Geology*, *17*, 404-407, 1989

Ratschbacher, L., W. Frisch, H -G. Linzer, and O. Merle, Lateral extrusion in the Eastern Alps, 2, structural analysis, *Tectonics*, *10*, 257-271, 1991.

Reusser, E., Phasenbeziehungen im Tonalit der Bergeller Intrusion, Ph.D. thesis, Eidg Tech. Hochsch., Zürich, Switzerland, 1987.

Rey, D , T. Quarta, P. Mouge, M Miletto, R Lanza, A. Galdeano, M.T. Carozzo, E Armando, and R Bayer, Gravity and areomagnetic maps of the western Alps Contribution to the knowledge on the deep structures along the Ecors-Crop seismic profile, in *Deep Structure of the Alps*, edited by F. Roure et al , *Mém. Soc. Géol. Fr.*, *156*, 107-121, 1990

Ring, U , L. Ratschbacher, and W. Frisch, Plate-boundary kinematics in the Alps Motion in the Arosa suture zone, *Geology*, *16*, 696-698, 1988.

Rosenberg, C , A Berger, C Davidson, and S.M. Schmid, Messa in posto del plutone di Masino-Bregaglia, Alpi Centrali, *Atti Ticinensi Sci. Terra Ser. spec.*, *1*, 31-39, 1994

Rosenberg, C., A. Berger, and S M. Schmid, Observations from the floor of a granitoid pluton A constraint on the driving force of final emplacement, *Geology*, *23*, 443-446, 1995

Roure, F., R. Polino, and R Nicolich, Early Neogene deformation beneath the Po plain: Constraints on post-collisional Alpine evolution, in *Deep Structure of the Alps*, edited by F Roure et al , *Mém. Soc. Géol. Fr.*, *156*, 309-321, 1990.

Rück, P., Stratigraphisch-sedimentologische Untersuchung der Schamser Decken, in *Die Schamser Decken, Teil 1, Beitr. Geol. Karte Schweiz*, *167*, 1-76, 1995.

Rutter, E.H , and K.H Brodie, Rheology of the lower crust, in *Continental Lower Crust*, edited by D M. Fountain et al., *Dev. Tectonics*, *23*, 201-267, 1992.

Schmid, S M., The Glarus overthrust. Field evidence and mechanical model, *Eclogae Geol. Helv.*, *68*, 247-280, 1975.

Schmid, S M , Ivrea zone and adjacent Southern Alpine basement, in *Pre-Mesozoic Geology in the Alps*, edited by J.F. Von Raumer and F. Neubauer, pp 567-583, Springer Verlag, New York, 1993.

Schmid, S M, and N Froitzheim, Oblique slip and block rotation along the Engadine line, *Eclogae Geol. Helv.*, *86*, 569-593, 1993.

Schmid, S M , and R Haas, Transition from near-surface thrusting to intrabasement decollement, Schlinig thrust, Eastern Alps, *Tectonics*, *8*, 697-718, 1989

Schmid, S M., A Zingg, and M Handy, The kinematics of movements along the Insubric line and the emplacement of the Ivrea zone, *Tectonophysics*, *135*, 47-66, 1987

Schmid, S M , H R Aebli, F Heller, and A Zingg, The role of the Periadriatic line in the tectonic evolution of the Alps, in *Alpine Tectonics*, edited by M.P. Coward, D. Dietrich, and R G. Park, *Geol. Soc. Spec. Publ. London*, *45*, 153-171, 1989

Schmid, S M , P Rück, and G. Schreurs, The significance of the Schams nappes for the reconstruction of the paleotectonic and orogenic evolution of the Penninic zone along the NFP-20 East traverse (Grisons, eastern Switzerland), in *Deep Structure of the Alps*, edited by F. Roure et al , *Mém Soc. Géol. Fr , 156*, 263-287, 1990.

Schmid, S M , O.A Pfiffner, and G Schreurs, Rifting and collision in the Penninic zone of Eastern Switzerland, in *Deep Structure of the Swiss Alps - Results from NFP/PNR-20*, edited by P. Heitzmann et al., Birkhäuser, Basel, Switzerland, in press, 1996

Schmutz, H., *Der Mafit-Ultramafitkomplex zwischen Chiavenna und Val Bondasca, Beitr. Geol. Karte Schweiz*, *149*, 73 pp , 1976.

Schönborn, G , Alpine tectonics and kinematic models of the Central Southern Alps, *Mem. Sci. Geol.*, *44*, 229-393, 1992

Schreurs, G , Structural analysis of the Schams nappes and adjacent tectonic units· Implications for the orogenic evolution of the Pennine zone in eastern Switzerland, *Bull. Soc. Géol. Fr.*, *164*, 415-435, 1993

Schreurs, G , Structural analysis of the Schams nappes and adjacent tectonic units in the Pennine zone, in *The Schams nappes*, part 2, *Beitr. Geol. Karte Schweiz*, *167*, pp 77-128, 1995.

Shelton, G , and J Tullis, Experimental flow laws for crustal rocks, *EoS Trans. AGU*, *62*(17), 369, 1981

Sinclair, H D, and P.A. Allen, Vertical versus horizontal motions in the Alpine orogenic wedge. Stratigraphic response in the foreland basin, *Basin Res.*, *4*, 215-232, 1992

Spillmann, P , Die Geologie des penninisch-ostalpinen Grenzbereichs im südlichen Berninagebirge, Ph.D thesis, Eidg. Tech Hochsch , Zürich, Switzerland, 1993

Stampfli, G , Le Briançonnais, terrain exotique dans les Alpes?, *Eclogae Geol. Helv , 86*, 1-45, 1993.

Stäuble, M , and O A. Pfiffner, Processing, interpretation and modeling of seismic reflection data in the Molasse basin of eastern Switzerland, *Eclogae Geol. Helv.*, *84*, 151-175, 1991a

Stäuble, M , and O A. Pfiffner, Evaluation of the seismic response of basement fold-and-thrust geometry in the Central Alps based on 2-D ray tracing, *Ann. Tectonicae*, *5*, 3-17, 1991b.

Stäuble, M., O A Pfiffner, and S B Smithson, Crustal structure and reflectivity of the Swiss Alps from three-dimensional seismic modeling, 1, Helvetic nappes, *Tectonics*, *12*, 911-924, 1993

Steck, A , and J.C Hunziker, The Tertiary structural and thermal evolution of

the Central Alps - Compressional and extensional structures in an orogenic belt, *Tectonophysics, 238*, 229-254, 1994.

Steinmann, M., Ein Beckenmodell für das Nordpenninikum der Ostschweiz, *Jahrb. Geol. Bundesanst. Wien*, 675-721, 1994.

Thöni, M., The Rb-Sr thin slab isochron method - An unreliable geochronologic method for dating geologic events in polymetamorphic terrains?, *Mem. Sci. Geol., 38*, 283-352, 1986

Thöni, M, and E Jagoutz, Isotopic constraints for eo-alpine high-p metamorphism in the Austroalpine nappes of the eastern Alps: Bearing on Alpine orogenesis, *Schweiz. Mineral. Petrogr. Mitt., 73*, 177-189, 1993.

Tietz, R, M. Handy, I Villa, and B Kamber, Strukturgeologische und radiometrische Untersuchungen an der Grenze Unterostalpin-Penninikum im Raume Piz Lungin und Piz dal Sasc (GR), paper with abstract presented at Schweizerisches Tektonikertreffen, Eidg Tech. Hochsch, Zürich, 1993

Trommsdorff, V., and P Nievergelt, The Bregaglia (Bergell) Iorio intrusive and its field relations, *Mem. Soc. Geol Ital., 26*, 55-68, 1983

Trommsdorff, V, G B Piccardo, and A Montrasio, From magmatism through metamorphism to sea floor emplacement of subcontinental Adria lithosphere during pre-Alpine rifting (Malenco, Italy), *Schweiz. Mineral. Petrogr. Mitt, 73*, 191-203, 1993

Trümpy, R, Die helvetischen Decken der Ostschweiz Versuch einer palinspastischen Korrelation und Ansätze zu einer kinematischen Analyse, *Eclogae Geol. Helv., 62*, 105-142, 1969.

Trümpy R, *Geology of Switzerland* A Guide Book, Wepf, Basel, Switzerland, 1980

Trümpy, R, Ostalpen und Westalpen - Verbindendes und Trennendes, *Jahrb. Geol. Bundesanst. Wien, 135*, 875-882, 1992

Valasek, P., The tectonic structure of the Swiss Alpine crust interpreted from a 2D network of deep crustal seismic profiles and an evaluation of 3-D effects, Ph D. thesis, 195 pp. and appendix, Eidg. Tech. Hochsch., Zürich, Switzerland, 1992.

Valasek, P, S Mueller, W Frey, and K Holliger, Results of NFP 20 seismic reflection profiling along the Alpine section of the European Geotraverse (EGT), *Geophys. J. Int., 105*, 85-102, 1991.

von Blanckenburg, F., Combined high-precision chronometry and geochemical tracing using accessory minerals Applied to the Central-Alpine Bergell intrusion (central Europe), *Chem. Geol., 100*, 19-40, 1992.

von Blanckenburg, F, and J H Davies, Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps, *Tectonics, 14*, 120-131, 1995

Wagner, G.A., G M Reimer, and E. Jäger, *Cooling ages derived by apatite fission-track, mica Rb-Sr and K-Ar dating: The uplift and cooling history of the Central Alps, Mem. Ist. Geol Mineral. Univ. Padova, 30*, 1977.

Wenk, H.R., The structure of the Bergell Alps, *Eclogae Geol. Helv., 66*, 255-293, 1973.

Wenk, H.R., and S.B Cornelius, Geologischer Atlas der Schweiz 1 25000, sheet 70 Sciora, Schweiz. Geol. Kommission, Bern, 1977

Wyss, R, Die Urseren-Zone Lithostratigraphie und Tektonik, *Eclogae Geol Helv., 79*, 731-767, 1986.

Ye, S., Crustal structure beneath the Central Swiss Alps derived from seismic refraction data, Ph D. thesis, 125 pp., Eidg Tech.

Hochsch. Zürich, Switzerland, 1992.

Ye, S., J. Ansorge, E. Kissling, and S. Mueller, Crustal structure beneath the eastern Swiss Alps derived from seismic refraction data, *Tectonophysics*, 242, 199-221, 1995.

Zanchi, A., S. Chiesa, and P.-Y. Gillot, Tectonic evolution of the Southern Alps in the Orobic chain: Structural and geochronological indications for pre-Tertiary compressive tectonics, *Mem. Soc. Geol. Ital., 45*, 77-82, 1990.

Ziegler, W., Geologische Studien in den Flyschgebieten des Oberhalbsteins (Graubünden), *Eclogae Geol. Helv., 49*, 1-78, 1956.

Zingg, A., M.R. Handy, J.C. Hunziker, and S.M. Schmid, Tectonometamorphic history of the Ivrea zone and its relationship to the crustal evolution of the Southern Alps, *Tectonophysics, 182*, 169-192, 1990.

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