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TRANSITION FROM NEAR-SURFACE THRUSTING TO INTRABASEMENT DECOLLEMENT, SCHLINIG THRUST, EASTERN ALPS

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Abstract. West directed thrusting along the Schlinig thrust amounts to a minimum displacement of 45 km. A discrete plane of brittle thrusting is observed in the frontal part, where the Ötztal unit overrides the sediments of the Engadine Dolomites. Both shortening of the more ductile Lower and Middle Triassic and very substantial stretching by domino-type normal faults in the brittle Upper Triassic dolomites are contemporaneous with, and caused by, thrusting. Extension is related to extrusion of parts of the sediments in the footwall of the Schlinig thrust. A relatively rapid transition into an intrabasement shear zone, which is as much as 2-km-thick, occurs farther to the east in a region where a paleotemperature of 300°C is indicated for Cretaceous metamorphism. Still farther to the east, localized shearing is transformed into a wider area affected by large-scale folding. This second transition corresponds to estimated temperatures in excess of 550°C. Since the changes in structural style and deformation mechanisms toward the hinterland go hand in hand with increasing metamorphic grade, we regard thrusting as contemporaneous with metamorphism. This view is supported by geochronological data. The age of thrusting and metamorphism (90 Ma) indicates very rapid heating after the deposition of the youngest sediments (Cenomanian) involved in Cretaceous deformation. Our data suggest that localized detachment along a discrete thrust plane and within broader mylonite zones cannot always be traced indefinitely to greater depth. The transformation of localized shearing into large scale folding indicates a fundamentally different deformational style for lower crustal levels.

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1. INTRODUCTION

In the Central and Eastern Alps the principal direction of thrusting has classically been considered to be top to the north, that is, in a direction perpendicular to the general strike of the Alpine chain [e.g. Tollmann 1977, 1987]. This widely accepted view formed an integral part of the classical nappe theory developed at the beginning of this century. Modern interpretations in the light of plate tectonics mostly consider pure N-S compression as a consequence of subduction of the European plate beneath the African (or Apulian) plate [Hawkesworth et al., 1975] or vice versa [Oxburgh, 1972].

However, careful mapping of the Engadine Dolomites, situated in the footwall of the Schlinig thrust, led Spitz and Dyhrenfurth [1914] to postulate top to the west thrusting at the beginning of this century. These heretical views were heavily criticised by Heim [1922]. Later they were completely forgotten, while Staub [1937] tried to explain the tectonics of the region within the rigid cylindrical framework which worked so well in the Central and Western Alps.

The idea of local top to the west thrusting reappeared again in more modern investigations [Brunel, 1980; Brunel and Geyssant, 1978; Schmid, 1973; Selverstone, 1988]. Ratschbacher [1986] first recognized that top to the west thrusting affected the entire Austroalpine nappe system. It is one of the aims of this contribution to add more evidence for top to the west thrusting during the Cretaceous orogeny (Eoalpine in the sense of Trümpy [1973], although we do not wish to deny top to the north thrusting during later movements. The mere existence of Tertiary sediments in the Engadine window documents that the previously deformed Austroalpine nappe system must have been carried in a northerly direction during the Tertiary. For a recent analysis of changing motions along the suture between Austroalpine and Penninic units the reader is referred to Ring et al.[1988].

Thrusting of the Ötztal basement nappe led to very complex deformations within the sediments of the footwall (Engadine Dolomites). The analysis of this deformation helps to constrain the amount and direction of movement along the Schlinig thrust. Furthermore, very substantial stretching is related to extrusion of parts of the sediments in the footwall of this thrust. The documentation of substantial local extensions in an overall compressional environment forms a second key part of this contribution.

The area of investigation also offers the unique opportunity to study the transition from near-surface thrusting along a discrete thrust plane into a kilometer-wide shear zone and finally into large-scale folding, as depth and metamorphic grade increase toward the hinterland. Because of subsequent differential uplift the trace of the thrust can be followed over some 70 km and into a region were amphibolite conditions prevailed during thrusting. Consequently, the third principal aim of this contribution is to describe this transition and to provide evidence against extrapolations of ramp and flat thrust geometries to greater depth or even as far as down to the Moho [e.g., Butler, 1986].

2. THE CENTRAL AUSTROALPINE UNITS WEST OF THE TAUERN WINDOW

Geographically, the investigated area depicted in Figure 1 is situated in the border region between Switzerland, Austria (Tyrol) and Northern Italy (Southern Tyrol). Geologically, the area is south of the Northern Calcareous Alps and north of the Periadriatic fault system (Tonale and Giudicarie faults). We use the term "Central Austroalpine", as defined by Trümpy and Haccard [1969], to denote those Austroalpine units south of the Northern Calcareous Alps which structurally overly Lower Austroalpine and Penninic units.

Three major basement units are mapped out in Figure 1: (1) the Silvretta basement north of the Engadine fault, (2) the Languard-Campo-Sesvenna basement south of the Engadine fault, and (3) the Ötztal basement between the Lower Engadine and Tauern windows. Subsequent to penetrative deformation and Variscan high-grade metamorphism these basement units formed part of the uppermost crustal levels of the Apulian continent, unconformably overlain by its Permo-Triassic cover. During the Alpine orogeny thrust sheets were completely detached from lower crustal levels, in many places with only minor Alpine reworking both in terms of metamorphism and penetrative deformation. A notable exception is the southeastern part of the Ötztal basement, where amphibolite facies conditions were reached during the Late Cretaceous [Thöni and Hoinkes, 1987], albeit with very minor Alpine deformations, according to previous workers [Helbig and Schmidt, 1978; van Gool et al., 1987].

The Permo-Mesozoic cover of these large basement thrust sheets is only preserved within spatially limited areas. Only at the western edge of the Silvretta basement is its cover preserved. A larger triangular-shaped sedimentary region occurs south of the Engadine fault (Engadine Dolomites). Parts of the Engadine Dolomites (Ortler unit, Figure 2) represent the original cover of the Campo basement, whereas other parts (Scharl-Unterbau) represent the original cover of the Sesvenna basement. The sedimentary cover of the Ötztal basement is confined to a region immediately west of the Tauern window (Brenner Mesozoics).

We consider the Schlinig thrust to represent a major crustal scale decollement along which the Ötztal basement overrode both the Languard-Campo-Sesvenna and the Silvretta basement units and their sedimentary cover. Previous workers already described this thrust along its frontal (western) part, where the Ötztal basement is clearly seen to override the Engadine Dolomites along a discrete thrust contact [Kellerhals, 1966; Stutz and Walter, 1983]. The existence of the Jaggl window (Figure 2) farther to the east [Hess, 1962; Thöni, 1973 ; van Gool et al., 1987] suggests that this thrust may be of more than local importance. However, problems arise in respect to its continuation both toward the SE and NE.

A discrete thrust plane no longer exists along the expected southeastward continuation of the Schlinig thrust across the Vinschgau valley (east of Schleis, Figure 2). This transformation from discrete thrusting into intrabasement decollement is the subject of a later chapter.

To the NE the Schlinig thrust is cut by the SW-NE trending Engadine fault which is of mid-Oligocene to Miocene age [Trümpy, 1972, 1977]. There the Ötztal basement is directly juxtaposed with the structurally much lower units of the Lower Engadine window (Figure 1). In our view this juxtaposition is due to substantial normal faulting along the Engadine fault. This normal faulting is associated with updoming and unroofing of the Engadine window. In an area SW of Schuls, the Silvretta basement is seen to wedge out toward the NE in map view (Figure 2). According to Wenk [1934], Eugster [1971, 1985], Cadisch et al. [1968], and our own observations the Silvretta basement finds its disrupted continuation in the Sesvenna basement which is situated south of the Engadine fault. This wedging is caused by an increasing amount of normal fault displacement toward the NE. Along the trace of the profile depicted in Figure 5b a vertical component of at least 4 km can be deduced along the SSE dipping (50°-60°) fault plane. Farther down the Inn valley the vertical component increases farther, and ultimately, the Ötztal basement comes to lie in direct contact with the Engadine window.

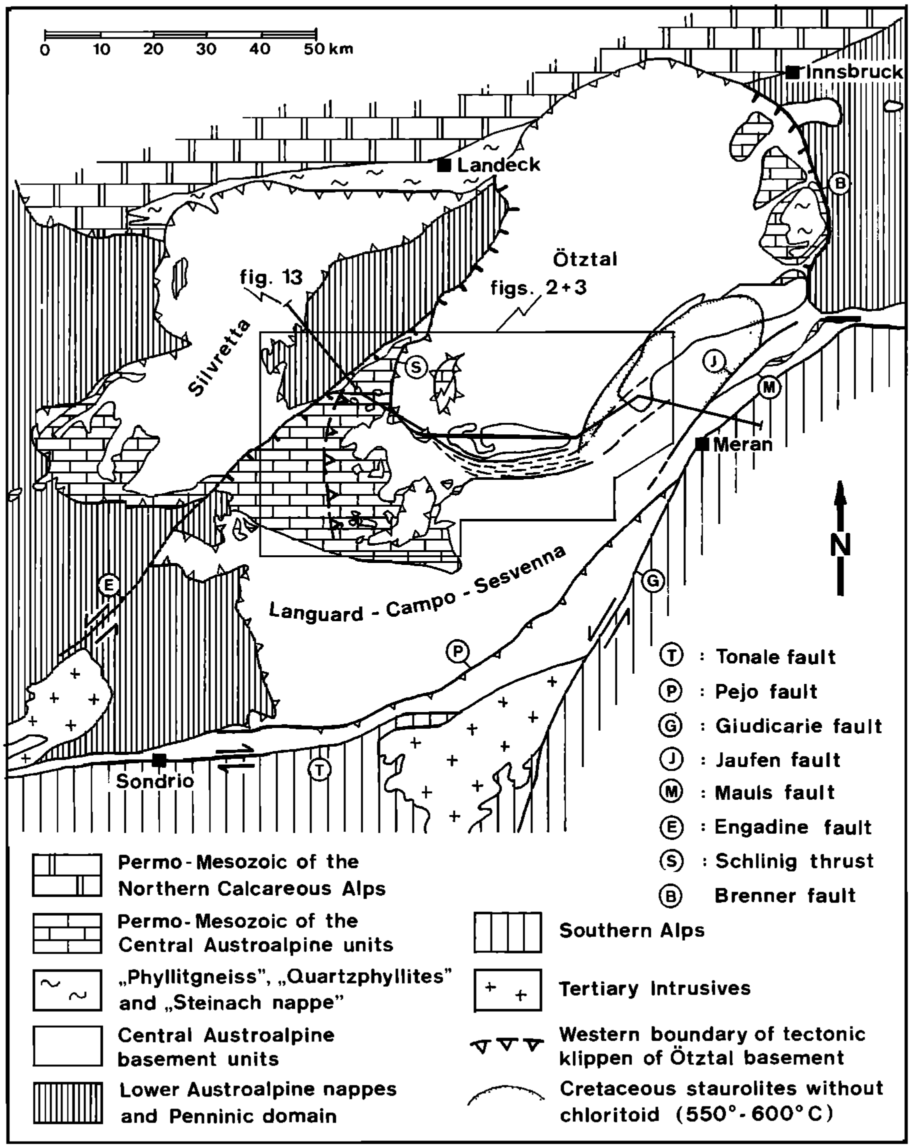

Fig. 1. Sketch map of the Central Austroalpine units west of the Tauern window.

Minor sinistral strike-slip components along the Engadine fault cannot be excluded. However, structural data collected in the upper Engadine valley by Liniger and Guntli [1988] indicate that this strike-slip offset is of the order of 1 km only, that is, substantially less than earlier estimates by Trümpy [1972, 1977].

Thus both Silvretta basement and Languard-Campo-Sesvenna basement formed a single lower thrust sheet in the Cretaceous, later dissected by the Engadine fault and updoming of the Engadine window. Possible former extensions of the structurally higher Ötztal thrust sheet NW of the Engadine fault have been removed by erosion. Thus we have to confine the discussion in the following chapters to a region SE of the Engadine fault.

3. DEFORMATION OF THE SEDIMENTS OF THE ENGADINE DOLOMITES IN THE FOOTWALL OF THE SCHLINIG THRUST

3.1. *Stratigraphy of the Engadine Dolomites*

The lithostratigraphy is briefly summarized in order to discuss important implications for tectonic style. Details on the stratigraphy are found in the papers by Dössegger and Müller [1976] and Dössegger et al. [1982]. The Permo-Triassic clastics (Münstertal Verrucano) unconformably overlie the Variscan basement and were deposited in late Variscan graben structures associated with volcanic activity in the Permian. These sediments and volcanics reach a thickness of up to 1 km in Val

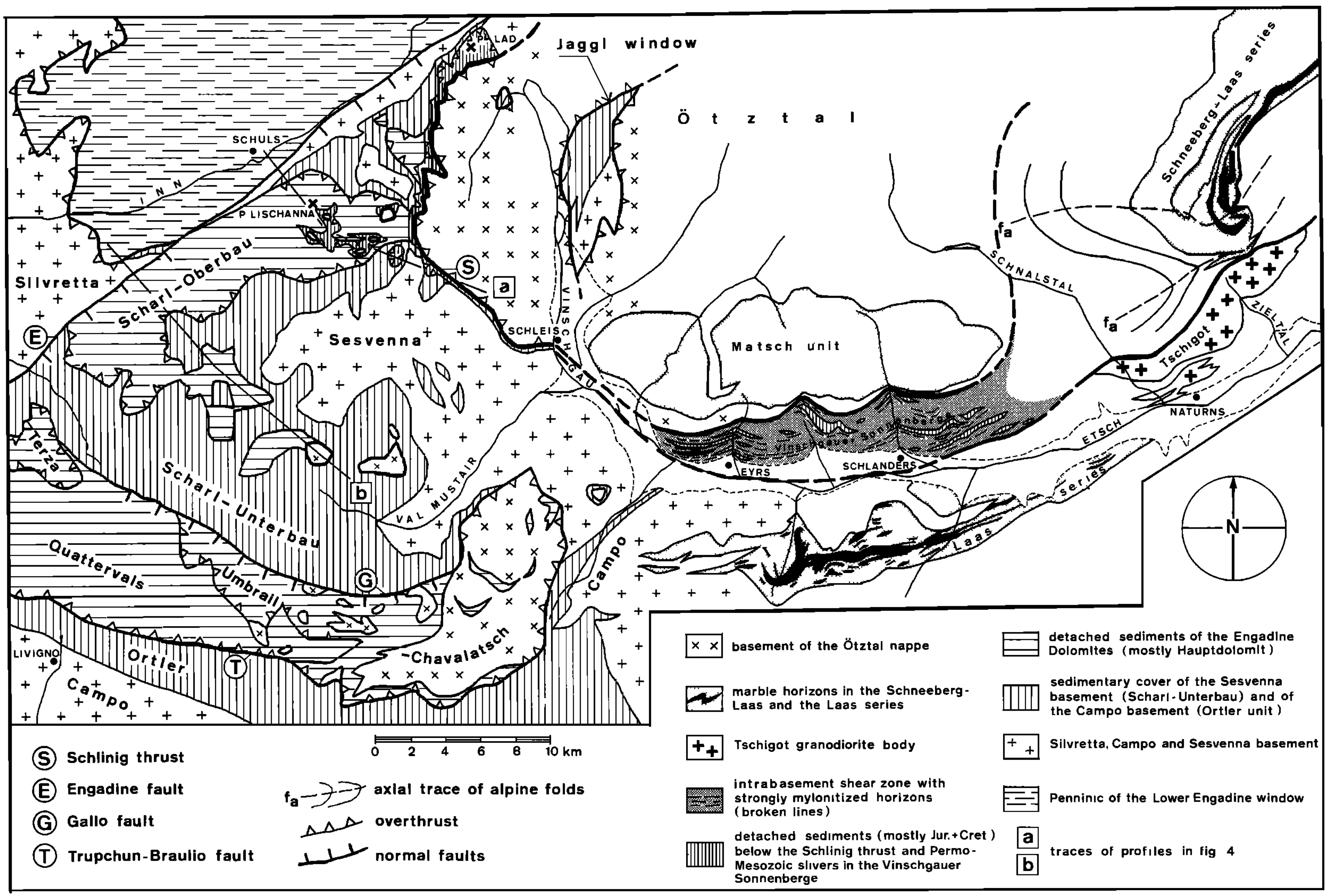

Fig. 2. Geological map of the Schlinig thrust and adjacent areas. For location see Figure 1.

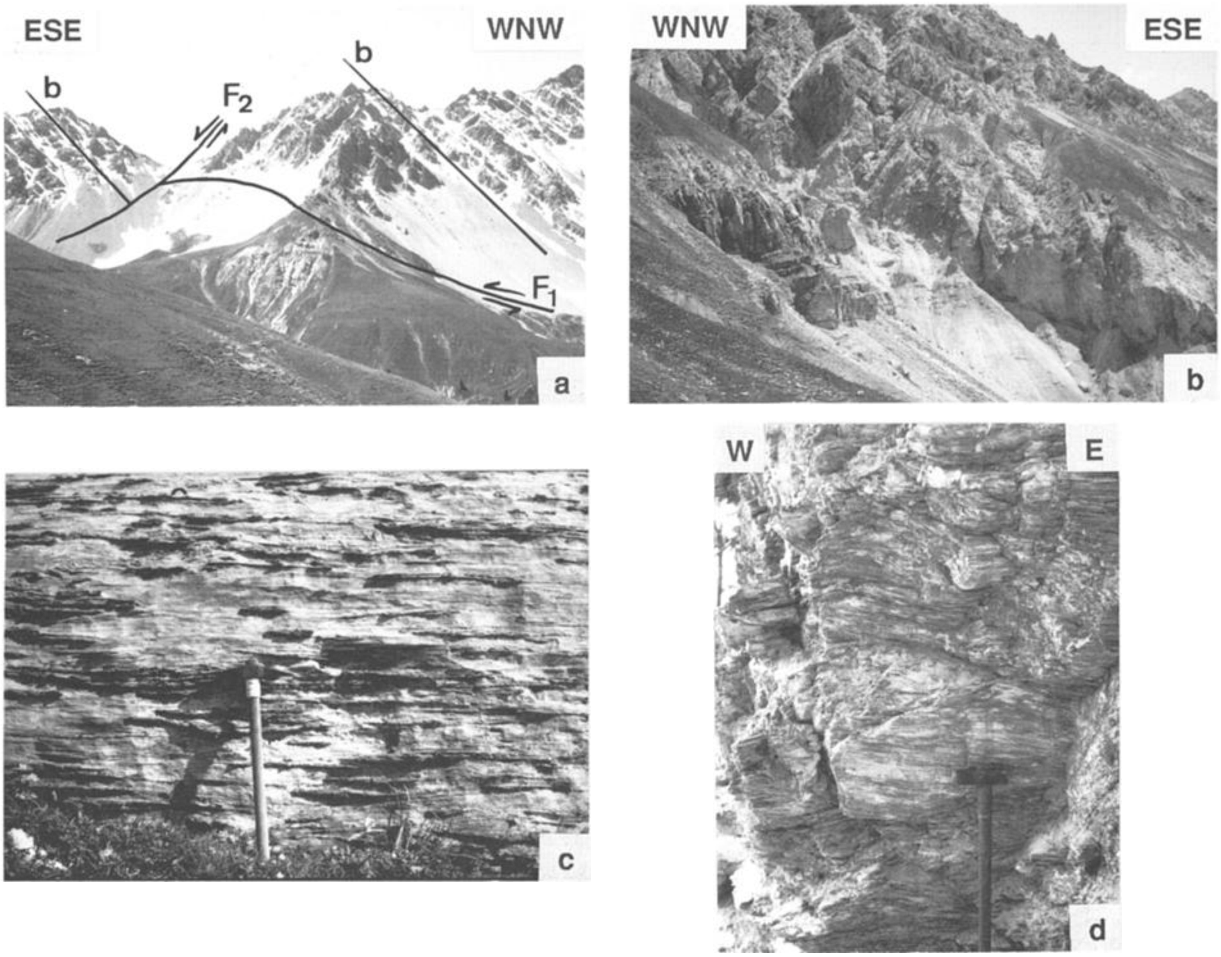

Fig. 3. Manifestations of brittle and ductile deformations related to the Schlinig thrust. (a) Second generation normal fault (F2), displacing older normal fault (F1). The older normal fault rotated through the horizontal into a gently WNW dipping orientation. Note angular discordance between the flat-lying Raibl Formation below normal fault (F1) and the WNW dipping dolomites of the Hauptdolomit (b indicates bedding). Locality, NW of Piz Foraz, compare Figure 5c). (b) Close up view of domino-type normal fault (F2 of Figure 3a) with angular discordance between Raibl formation (footwall) and Hauptdolomit group (hanging wall). (c) Dismembered and transposed isoclinal folds within silicious limestones of Jurassic age. Fold axes rotated into parallelism with the transport direction a few meters below the Schlinig thrust. Locality, uppermost Schlinig valley, NW of Schleis. (d) Mylonitized Augengneisses exhibiting the very strong stretching lineation typical for the intrabasement shear zone.

Müstair, whereas in other areas, such as below the Schlinig thrust in the Schlinig valley NW of Schleis (Figure 2), they are missing. The transition into the carbonate facies, dominating in the Triassic formations, is marked by a very characteristic alternation of siliciclastic sandstones, carbonate bearing sandstones, dolomites, limestones, and thin evaporitic horizons. This so-called Fuorn Formation defines a first potential decollement horizon and plays a key role in recognizing remnants of the sedimentary cover in the Vinschgauer Sonnenberge north of Eyrs and Schlanders (Figure 2). The carbonates of the Lower and Middle Triassic reach a thickness of only about 250 m and their tectonic style is characterized by folding and minor thrusting.

The ductile evaporites of the Raibl Formation at the base of the Upper Triassic define another very important decollement horizon. Above, the rigid dolomites of the Upper Triassic (Hauptdolomit group) reach a thickness of up to 2 km. This dolomite group is always completely detached from the older sediments (Figures 3a and 3b). The younger postrift sediments (Jurassic and Early Cretaceous) are relatively thin (at most a few hundred meters) and very ductile (Figure 3c). They are the only sediments which always exhibit a well-defined schistosity and stretching lineations.

This results in a situation whereby the very competent Hauptdolomit group with its impressive thickness is sandwiched between more ductile horizons.

3.2 *The Main Tectonic Units of the Southern Engadine Dolomites*

Staub [1937] and his students made several different attempts to subdivide the Engadine Dolomites into a series of nappes. However, the tectonic subdivisions within the Engadine Dolomites are merely caused by imbrication of younger sediments detached above the Raibl Formation. The tectonic scheme presented in Figure 2 is largely based on later work by Eugster [1971], Karagounis [1962], Schmid [1973], Somm [1965], and Trümpy and Haccard [1969].

Only in the Ortler unit and the Scharl Unterbau (Figure 2) is a sedimentary contact between basement and cover preserved, although strongly tectonized in many places. Decollement in the Raibl beds and in the footwall of the Schlinig thrust led to the imbrication of allochthonous thrust sheets. These Upper Triassic imbricates can be grouped into the following four units (Figure 2): Scharl Oberbau, Terza, Quattervals, and Umbrail-Chavalatsch units.

One of these units (Umbrail-Chavalatsch) forms an imbricate zone composed of (1) Raibl Formation and Hauptdolomit detached from the Scharl Unterbau, and (2) slices of basement. Schmid [1973] revived the ideas of Spitz and Dyhrenfurth [1914] and provided evidence that these basement slices were derived from the structurally higher Ötztal unit during top to the west thrusting. The geographic position of these erosional relics of the Ötztal basement (Figure 2) indicates that the Schlinig thrust originally covered most, if not all, of the Engadine Dolomites, including the Ortler unit.

Unfortunately, these older detachments, related to thrusting of the Ötztal unit, are severely overprinted by younger (Tertiary?) SW directed movements along the Gallo normal fault and the Braulio-Trupchun thrust and, additionally, the formation of NW-SE trending large-scale open antiforms and synforms (see Figure 4). As a consequence, not much can be said any more about the original geometric configuration in the footwall of the Schlinig thrust in this southern part of the Engadine Dolomites.

3.3. *Deformation in the Footwall of the Schlinig Thrust in the Northern Engadine Dolomites*

North of the Gallo normal fault (Figure 2) older structures are much better preserved. Here we are in a better position to discuss direct relations between movement along the Schlinig thrust and deformation of the sediments in the footwall.

Groups of isolated klippen of the Ötztal basement are shown in Figure 2. Because of the existence of these klippen, and with the help of a contour map of the Schlinig thrust north of Schleis [Stutz and Walter, 1983, Figure 13] the position of the discrete thrust plane at the base of the Ötztal basement depicted in Figures 5a and 5b is well constrained.

It is evident from the profiles (Figure 5) that the sediments of the Engadine Dolomites wedge out to the SE and ESE. These sediments are sliced into three major tectonic units. A highest tectonic unit largely consists of detached Jurassic and Lower Cretaceous sediments (Figures 2 and 3c), but it also contains slivers of basement and Lower and Middle Triassic sediments which must have been detached from the footwall of the Schlinig thrust (Scharl Unterbau) beyond the SE termination of the profiles [Stutz and Walter, 1983]. The Hauptdolomit, the intermediate stratigraphic formation, is missing within this highest tectonic unit. This rigid Hauptdolomit formation must have been tectonically isolated from the other more ductile sediments, originally below and above it, by a process of extrusion described below. Mader [1987] found evidence for an inversion of a large part of the stratigraphical sequence within the Jurassic and Cretaceous in the region of Piz Lischanna. These sediments represent the overturned limb of a highly sheared syncline below the Schlinig thrust indicating that the frontal parts of the Ötztal unit must have moved much farther to the west or NW, beyond the present day position of the Engadine Line.

The Hauptdolomit, together with Jurassic breccias found in the Lischanna group [Mader, 1987], forms the so-called Scharl Oberbau, an intermediate tectonic unit which is completely detached from the older cover along the Raibl evaporites. This Hauptdolomit is very substantially stretched in the SE but shortened by thrusting and incipient folding in the NW of the profiles depicted in Figure 5. This extension leads to spectacular domino structures in the region of Piz Foraz and Piz Tavrü (Figures 5c, 3a and 3b). The geometry of these domino structures is very reminiscent of similar structures within the core complexes of the western United States [Miller et al., 1983]. The rotation of planar normal faults was so severe (one of the faults below Piz Foraz in Figure 5c is now in a horizontal attitude) that new generations of normal faults have been created (Figure 3a).

Taking the average dip of the normal faults to be 13° and that of the beds to be 38° (Figure 6), a crude estimate of the total stretch indicates a value for $1+e = 3.45$ for the region depicted in Figure 5c. Although some of this stretching could be attributed to the formation of a passive continental margin in the Early Jurassic [Bally et al., 1981, Froitzheim, 1988], the amount of stretching is far in excess of what can be expected for a continental margin [Le Pichon and Sibuet, 1981]. We propose that this stretching results from extrusion of the rigid Hauptdolomit in a northwesterly direction between the ductile sediments in the hanging wall of the dominos (uppermost tectonic unit) and the ductile Raibl Formation in the footwall. Thereby flow within the ductile strata could account for differential movements on top and at the base of the dominos and for taking up strain incompatibility problems arising at the edges of the dominos.

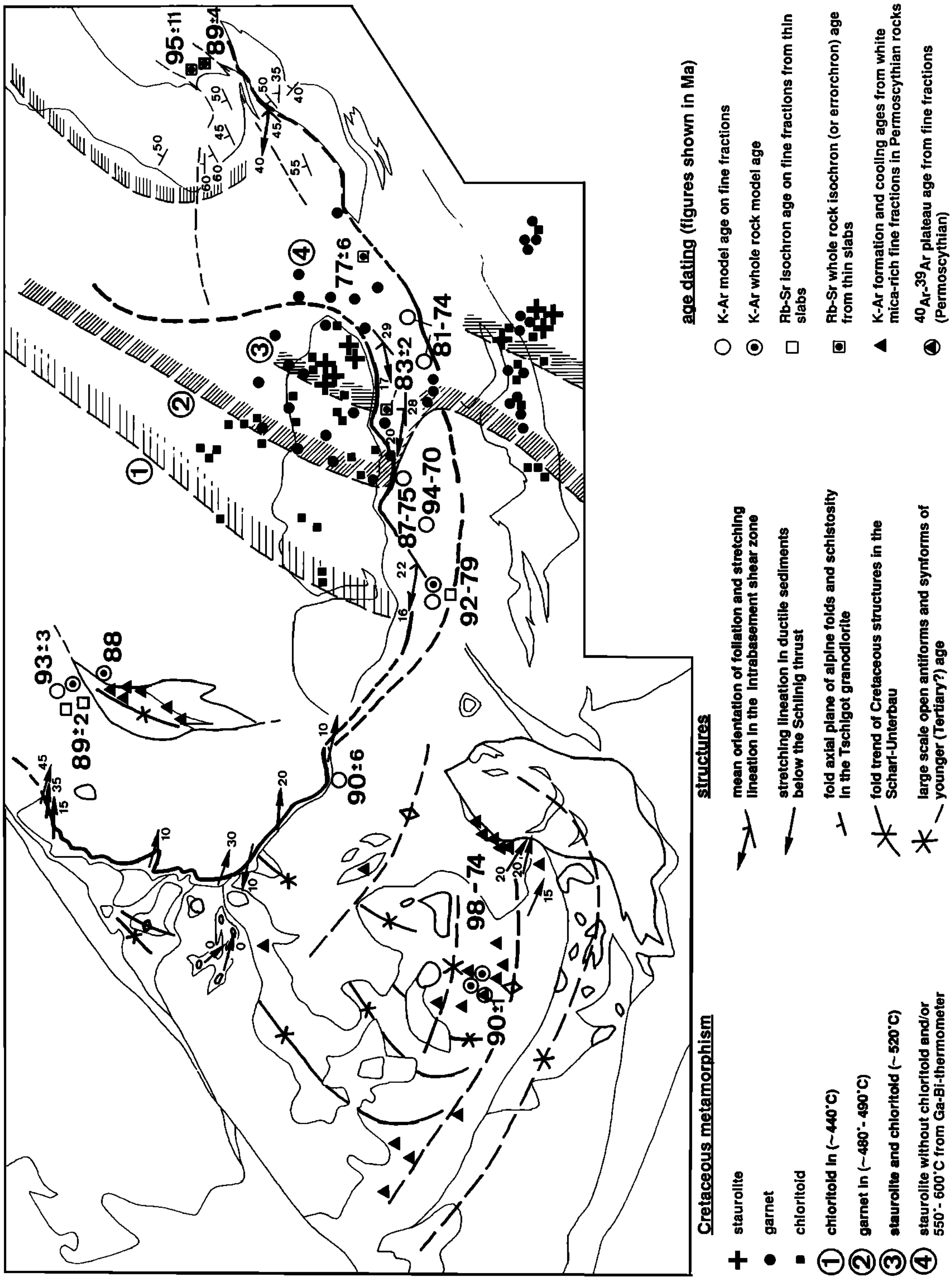

Fig. 4. Petrological, structural, and geochronological data for the area depicted in Figure 2. The mineral zone boundaries within the Ötztal unit are partly based on the work of Purtscheller et al. [1987]. Geochronological data are taken from the work of Thöni [1980a,b, 1981, 1983, 1986], and Thöni and Hoinkes [1987].

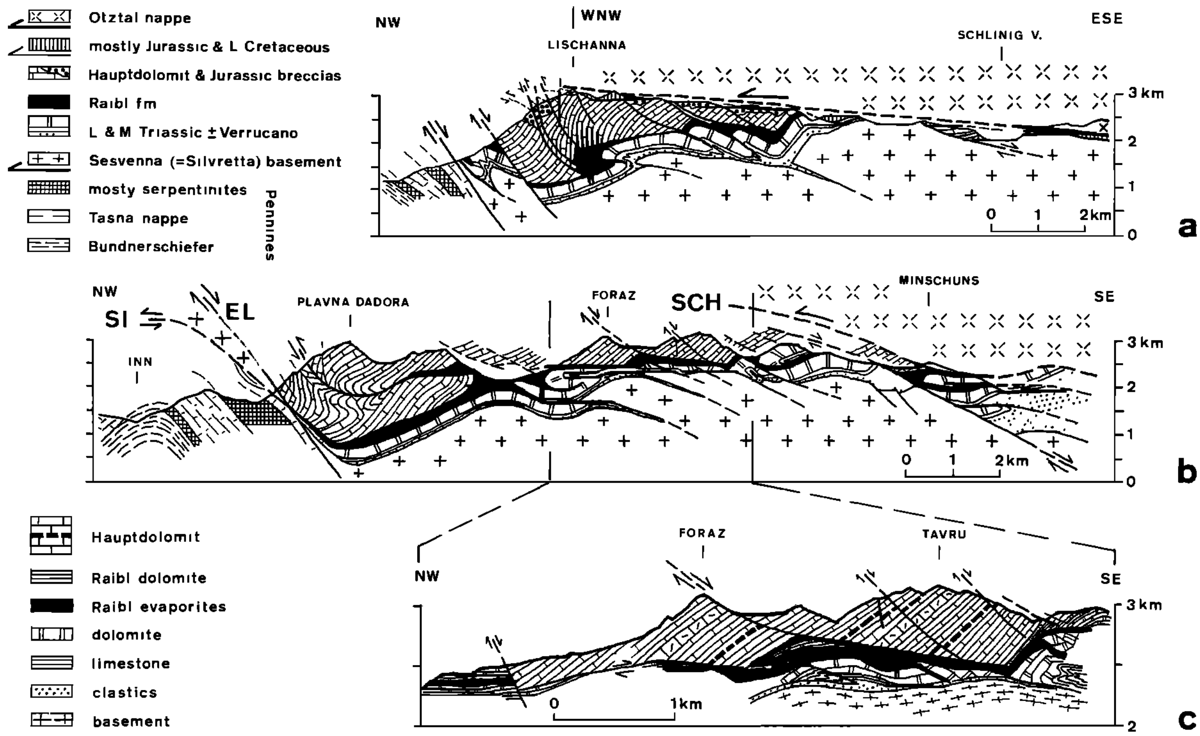

Fig. 5. Profiles through the Engadine Dolomites. (a) and (b) Traces of these profiles are indicated in Figure 2. (c) This profile depicts a detail from Figure 5b, constructed on the basis of data by W. Klemenz (unpublished data, 1967). SCH, Schlinig thrust; EL, Engadine fault; SI, basal thrust of the Silvretta Basement onto the Engadine window.

Figure 6 illustrates that domino style extension does not necessarily lead to a small component of shearing opposite to the expected sense of shear (Figure 6a) if simultaneous operation of bedding plane parallel slip is admitted (Figure 6b). With an initial angle of 70° between bedding and fault planes the resulting deformation is one of pure shear. On a much smaller scale a geometrically similar mechanism, often referred to as the bookshelf mechanism, operates within rigid clasts

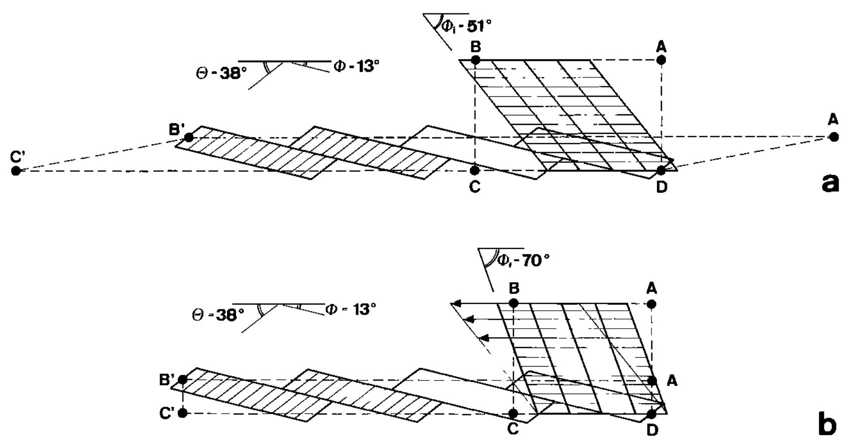

Fig. 6. Two possible kinematic restorations of the domino structure within the Hauptdolomit, as depicted in Figure 5c, assuming an average inclination of θ=38° for bedding and ϕ=13° for the faults. This geometry leads to a stretch of $1+e = \sin(\theta+\phi)/\sin\phi = 3.45$ in a horizontal direction. (a) Restoration without bedding parallel slip (ϕ_1: initial dip of normal fault). (b) Restoration allowin for bedding plane parallel slip.

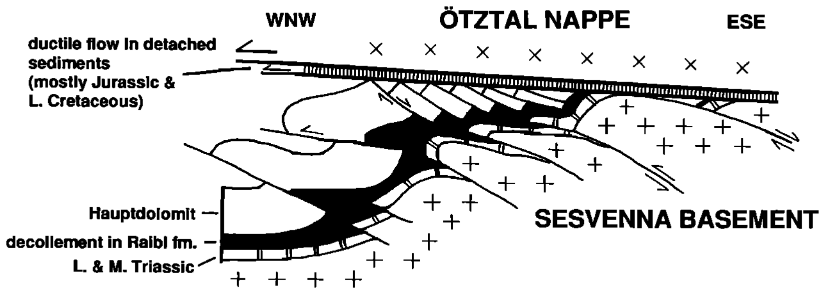

Fig. 7. Schematic sketch of the profiles depicted in Figure 5, illustrating contemporaneous stretching and shortening within the Hauptdolomit, as a result of extrusion below the Schlinig thrust. The effects of the later Engadine line have been removed.

of feldspar or mica in sheared mylonites [Simpson and Schmid, 1983, Figure 9].

The lowermost tectonic level (Scharl Unterbau) is characterized by shortening all along the profiles of Figures 5a and 5b. Fold axes exhibit the NE-SW strike typical for the NE Engadine Dolomites. Folding is associated with minor thrusting which affects the Sesvenna basement and locally leads to the creation of hanging wall antiforms in the basement (Figure 5a). At a later stage the previously shortened Scharl Unterbau was also affected by extension along ESE dipping normal faults within the SE portion of the profiles (Figures 5a and 5b).

The idea that severe extension within parts of the Hauptdolomit group is contemporaneous with shortening in other areas and due to inhomogeneous deformation in the footwall of the advancing Schlinig thrust is schematically illustrated in Figure 7. The principal argument in favor of such a view is the observation that extension is largely confined to the Hauptdolomit Group. Extension only occurs in a region to the ESE of the profile where the Hauptdolomit completely wedges out between younger and older beds. In the frontal area, where more space is left between the two basement units, we observe a transition into shortening within the same Hauptdolomit group. Near this transition no overprinting relationships between shortening and extension can be found, therefore both must be contemporaneous.

In a strict sense Stutz and Walter [1983] correctly argue that the compressional features within the Scharl Unterbau predate the Schlinig thrust because the latter cuts across preexisting structures in the Scharl Unterbau. However, we prefer a model of continuous deformation in the footwall of this thrust. During an initial stage, compressional deformation affects the Sesvenna basement and the Scharl Unterbau in front of the advancing Ötztal basement. Subsequently, the Scharl Oberbau becomes completely detached. It will be stretched in the footwall of the Ötztal basement above preexisting highs of the Sesvenna basement (ESE in Figure 7) or shortened above preexisting troughs (WNW in Figure 7). Finally, deformations in the footwall are concentrated within the highly sheared highest tectonic unit. This then leads to the final planar thrust plane which cuts across earlier structures.

This scenario implies out of sequence thrusting. Deformation in the footwall (Sesvenna basement and Scharl Unterbau) predates final thrusting in the hanging wall (Schlinig thrust). Out of sequence thrusting may be more common than usually assumed and is also observed in the Helvetic nappes of Eastern Switzerland (Glarus thrust [Schmid, 1975]).

3.4 *Indicators for The Transport Direction Within the Sediments of the Engadine Dolomites*

The strike of the compressional structures within the Scharl Unterbau (NE-SW) indicates a transport to the NW. In view of the observation that the folds in the Scharl Unterbau are fairly open and lack a penetrative cleavage, such an assumption seems justified. Furthermore, the strike of the normal faults in the Scharl Oberbau suggests extension in a northwesterly direction.

However, the stretching lineations within the penetratively deformed post-Triassic sediments of the uppermost tectonic unit and within penetratively deformed Verrucano sediments below the Umbrail-Chavalatsch unit [Schmid 1973] all indicate stretching to the west or WNW (Figure 3). Stutz and Walter [1983] carried out a detailed structural analysis within Jurassic limestones immediately below the Schlinig thrust. They found open N-S oriented folds away from the immediate contact with the Ötztal basement. Toward the thrust contact, strain intensity increases, and the axes of highly attenuated folds (Figure 3c) are found to be progressively reoriented into parallelism with the west to WNW trending stretching lineation.

Unfortunately, all attempts to corroborate the idea of top to the west shearing with sense of shear criteria within these sediments were unsuccessful. Sense of shear criteria indicating top to the west transport were only found within cataclasites and mylonites along the thrust contact and along the eastern continuation of the Schlinig thrust (see next section).

In summary, the orientation of the domino structures in the Hauptdolomit and the NW facing folds in the Scharl Unterbau suggest initially NW directed thrusting. The final movements, as indicated by the stretching lineations within the highest tectonic unit (Figure 4) are toward the west or WNW. This implies a sinistral rotation of the Ötztal basement during thrusting.

4. CHANGES IN STRUCTURAL STYLE AND DEFORMATION MECHANISMS ALONG THE SCHLINIG THRUST

4.1 *The Frontal Part of the Schlinig Thrust*

The Schlinig thrust is exposed as a razor sharp contact at the base of the Ötztal basement in its frontal part (NW of Schleis, Figure 2). Intense Alpine deformation within the Ötztal basement is restricted to a narrow zone (2-3 m thick) at the thrust contact, where Riedel shears within cataclasites indicate top to the west shearing (Figure 8a). For all minerals the main deformation mechanism is grain refinement by cataclasis. Quartz locally exhibits signs of intracrystalline plasticity (Figure 8b) although its main deformation mechanism is cataclasis as well. Alpine deformation is restricted to a weak cataclastic overprint away from the thrust contact. This finding is supported by geochronological evidence [Hoinkes et al., 1982] suggesting that within both the hanging wall (Ötztal basement) and the footwall (Sesvenna basement) all the major ductile structural elements such as foliations, folds, and lineations are of pre-Alpine age in this frontal part of the Schlinig thrust.

4.2. *The Intrabasement Shear Zone of the Vinschgauer Sonnenberge*

The eastern continuation of the Schlinig thrust is covered by Quaternary deposits for about 8 km along strike and reappears in the form of a wide intrabasement shear zone near Eyrs (Figure 2). Therefore the transition into this shear zone cannot be observed.

Lithologically, this up to 2-km-thick shear zone has been recognized and mapped as a belt of low-grade schists and phyllites by many previous workers, but only Hammer [1931] and Thöni [1980a] assumed that some of the constituents of this belt represented clastics from the basal Permo-Triassic cover of the Engadine Dolomites. A very characteristic association of (1) green chloritic schists with isolated carbonate nodules, (2) green-white sericitic schists, (3) carbonate-rich red-brown metapelites, (4) thin (20-200 cm) layers of calcite and dolomite marbles, and (5) Fe-rich dark slates have been mapped out as Permo-Mesozoic slivers in Figure 2.

We regard these lithologies as the strongly deformed and progressively metamorphosed equivalents of the Triassic Fuorn Formation for the following reasons:

1. They show evidence for only one (Cretaceous) metamorphic event, while in this region both Ötztal and Campo basements are polymetamorphic [Hoinkes et al., 1982].
2. There are strong lithological similarities with the Fuorn Formation at the base of the Triassic carbonates, both in terms of individual lithologies and the association of lithologies. For the recognition of this formation, detrital quartz grains with resorption tubes play a key role (Figure 8c). Quartz with resorption tubes is diagnostic for Permian volcanics which have been redeposited in the Verrucano and Fuorn formations.
3. The occurrence of this lithological association is confined to the strongly deformed shear zone and has not been found within the Variscan basement. Sediments younger than the Fuorn Formation are missing. They were detached, and some of them are found farther to the west and NW, as higher tectonic units of the Engadine Dolomites.

The upper limit of the intrabasement shear zone locally reaches the base of the Matsch unit (characteristic association of metasediments mapped out in Figure 2). However, the emplacement of this allochthonous subunit of the Ötztal basement is older and unrelated to the Schlinig thrust [Haas, 1985]. It is not possible to decide how much of the Variscan basement, which constitutes most of the rock volume within the shear zone, has been derived from the footwall or the hanging wall because of the close lithological similarities between the Campo and Ötztal basements in the immediate vicinity of the shear zone. Granitic augengneisses and monotonous metasedimentary schists predominate.

The deformational style within the shear zone is characterized by large variations in strain intensity. Less deformed pods of dominantly augengneiss are surrounded by discontinuous sheets of mylonites and phyllonites which form an anastomozing network. The dominant structural element is the ubiquitous E-W oriented stretching lineation (Figures 3d, 9a, and 9c). The foliation exhibits a variable dip to the north (Figures 9a and 9c). The average dip to the north increases from 21° to 29° toward the east (average dip indicated in Figures 4, 9a, and 9c).

Both fairly open and isoclinal folds have their axis parallel to the stretching lineation (Figures 9b and 9d). The parallelism of isoclinal folds and stretching lineation is typical for mylonite belts and often results from the passive rotation of earlier buckle folds, as a result of large shearing strains [Escher and Watterson, 1974]. The open folds are more difficult to interpret. We found no evidence for a later overprint which could have produced them. Therefore we interpret that these open folds were caused by buckling instabilities within less-deformed pods which formed as a result of the earlier (pre-Alpine) foliation not being parallel to the shear zone boundary (see discussion by Malavieille [1987]). Later structures are only sporadically developed as open folds or kink bands perpendicular to and overprinting the stretching lineation. Thin cataclastic horizons parallel to the main Alpine schistosity are restricted to a few horizons within the intrabasement shear zone.

Very consistent information on the sense of shear was obtained from quartz textures [Simpson and Schmid, 1983]. The X ray data presented in Figure 10 indicate top to the west shearing. This

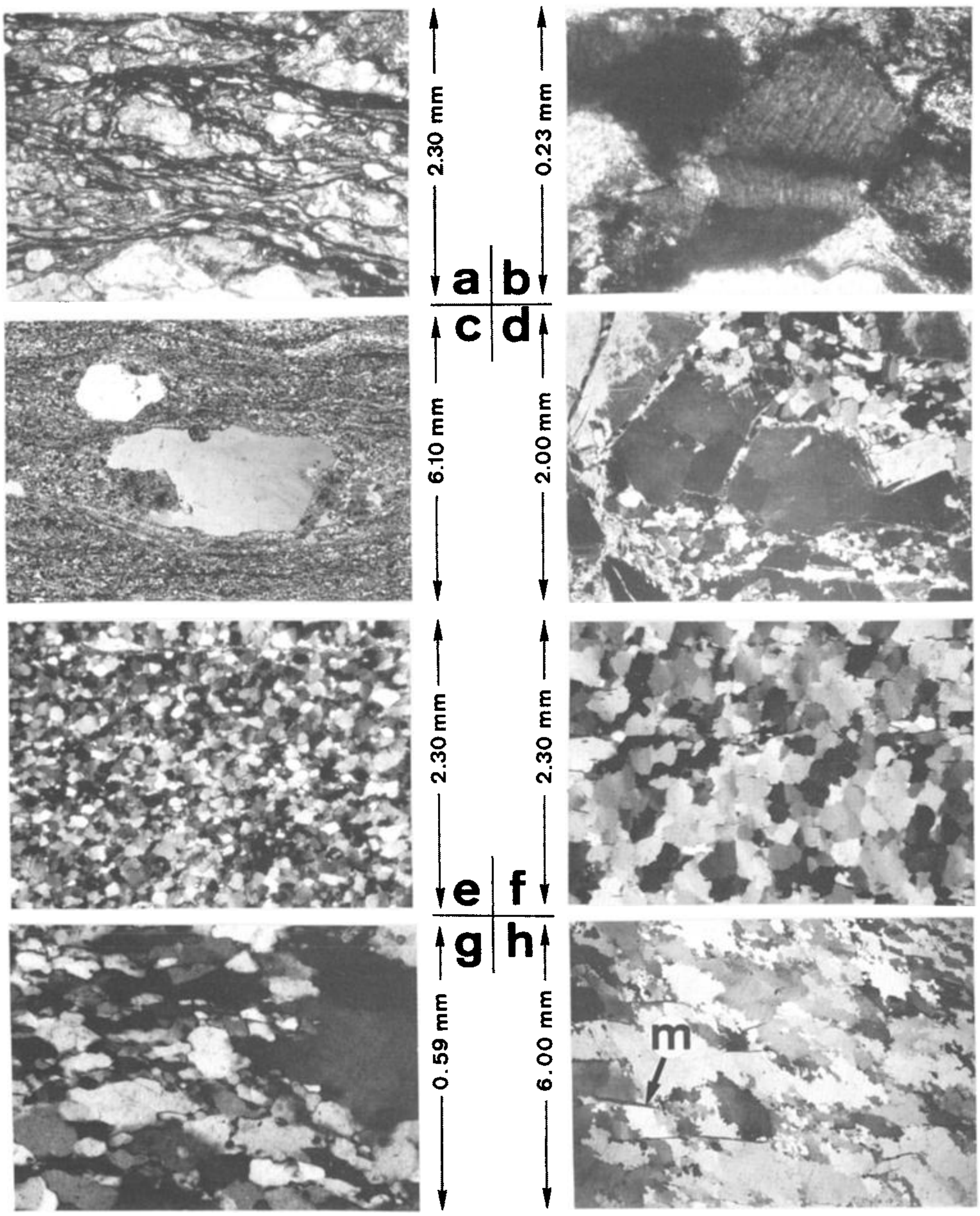

Fig. 8. Micrographs made with crossed polarizers (except Figure 8a). (a) Augengneiss cataclasite, frontal part of Schlinig thrust near Piz Lad. Composite foliation with Riedel shears indicating top to the west shearing (sinistral in respect to micrograph). (b) Bent deformation lamellae indicating incipient plasticity without recovery or recrystallization in quartz from cataclasite depicted in Figure 8a. (c) Detrital quartz grain with resorption tubes. Fuorn Formation; intrabasement shear zone near Eyrs. (d) Broken feldspars from augengneiss; intrabasement shear zone near Eyrs. (e) Dynamic recrystallization by the progressive subgrain rotation mechanism in quartz mylonite near Eyrs. Estimated temperature of metamorphism is 400°C. Quartz texture of the same specimen is depicted in Figure 10a. (f) Incipient dynamic grain boundary migration in quartz mylonite from near Schlanders. Estimated temperature of metamorphism is 500°C. Quartz texture of the same specimen is depicted in Figure 10b. (g) Recrystallized feldspar in mylonitic augengneiss 4 km NE of Schlanders. Estimated temperature of metamorphism is 530°C. (h) Oblique grain-shaped fabric in quartz mylonite, from the NW rim of the Tschigott granodiorite, indicating top to the west shearing (sinistral in respect to micrograph). The macroscopic foliation runs E-W and parallel to the shape-preferred orientation of micas (marked "m"). Dynamic recrystallization by grain boundary migration is associated with significant grain growth. Estimated temperature of metamorphism is 600°C. Quartz texture of the same specimen is depicted in Figure 10d.

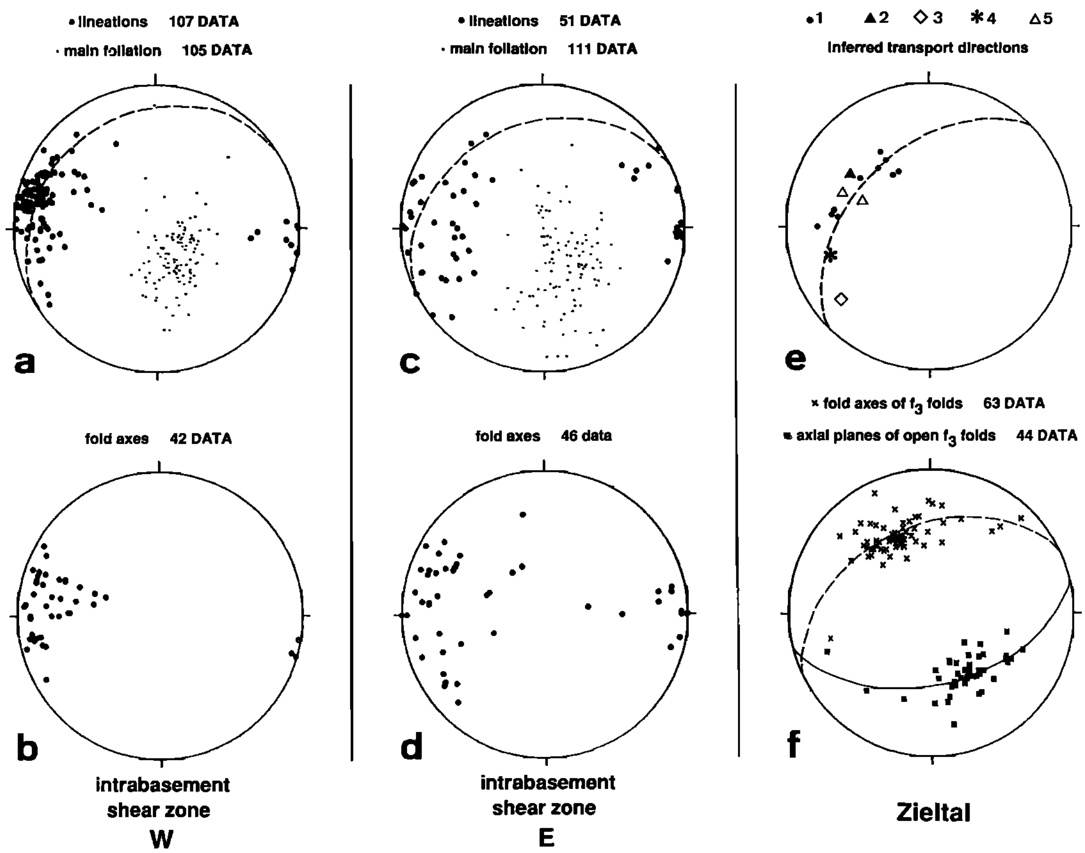

Fig. 9. Stereographic projection (equal area, lower hemishere) of structural data from the western and eastern part of the intrabasement shear zone in the Vinschgau and from a traverse along the upper Zieltal. (a) and (c) Stretching lineations and poles to the main foliation. Dashed great circle indicates the mean orientation of the foliation. (b) and (d) Fold axes of both open and isoclinal folds. (e) Inferred transport direction. The symbols are labeled and refer to (1) stretching lineations in mylonites at the NW rim of the Tschigott granodiorite, (2) stretching lineation of specimen 8670 yielding top to the west shear (compare Figures 8h and 10d), (3) top to the west shear bands in mylonites, (4) top to the west transport direction inferred from curving foliation within Tschigott granodiorite, and (5) transport direction inferred from folded lineations around f3 folds. Great circle defines the mean orientation of the mylonitic rim of the Tschigott granodiorite. f) Axial planes and f3 fold axes. There is considerable scatter of f3 fold axes along a great circle, represented by the mean orientation of the axial planes (dashed line). At the same time the axial planes fan around the mean orientation of the fold axes (solid line indicates plane normal to the mean orientation of fold axes).

finding was corroborated by additional X ray and U stage work and also by quickly assessing the asymmetry of the c axis pattern by inserting a gypsum plate. Within a total of 30 analysed specimens only 2 indicated inconsistent senses of shear.

The transition into the broad shear zone near Schleis coincides with a change in the deformation mechanism operating in quartz. The quartz textures presented in Figure 10 indicate <a> slip on the basal plane, the rhombs, and the prisms [Schmid and Casey, 1986]. The microstructures suggest that intracrystalline plasticity is associated with recovery and dynamic recrystallization by the subgrain rotation mechanism. The average grain size of equant recrystallized grains systematically increases from around 150 mm near Eyrs in the west to about 600 mm near Schlanders in the east (Figures 8e and 8f). This increase in grain size primarily reflects a decreasing deviatoric stress [Schmid, 1982] and, indirectly, increasing temperatures during deformation. In the western portions of the shear zone (near Eyrs), feldspars are broken (Figure 8d) and white micas are kinked. Farther to the east (near Schluderns) dynamic recrystallization is observed in feldspar as well (Figure 8g).

These microstructures reflect changes in the deformation mechanism and indicate increasing temperatures toward the east during deformation. The transition from dominantly cataclastic behavior of quartz into intracrystalline plasticity

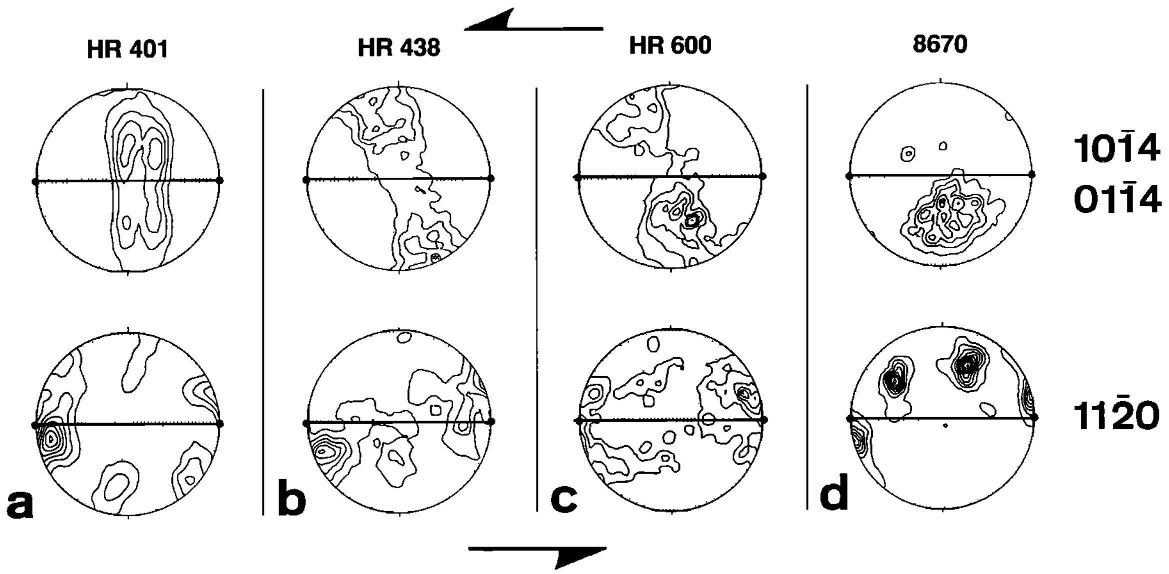

Fig. 10. X ray texture goniometer data from representative quartz-rich mylonites. The features of the pole figures (1014) and (0114) closely approximate those for the c axis, the a direction (1120) represents the dominant slip direction in quartz. All specimens are oriented for easy slip parallel to the a direction [Schmid and Casey, 1986] and indicate top to the west shearing. Specimens from the intrabasement shear zone (compare Figures 8e and 8f) collected near (a) Eyrs and (b,c) Schlanders. Contour interval is 1.0 in terms of a uniform distribution. (d) Specimen depicted in Figure 8h, parallel to the a direction, indicating dominant slip on the rhomb. Contour intervals are 2.0 in terms of a uniform distribution.

associated with dynamic recrystallization is very rapid. It must occur within a distance of 8 km between Schleis and Eyrs (Figure 2), thus over a small temperature interval. The linear plot of differential stress versus temperature, based on experimentally derived flow laws for quartz [Suppe, 1985, Figures 4-29, and references therein], indicates that this transition is expected to occur within a small temperature interval somewhere below 300°C.

4.3. *The Transition From an Intrabasement Shear Zone into a Zone of Large-Scale Folding*

In an eastward direction it becomes increasingly more difficult to map out the limits of this intrabasement shear zone of the Vinschgauer Sonnenberge. Identifiable Permo-Mesozoic slivers are absent. The grade of Cretaceous metamorphism becomes comparable to that of Variscan metamorphism, and therefore Alpine structures can no longer be distinguished from pre-Alpine structures with the help of the associated retrograde overprint. Thus we were unable to continuously trace this shear zone farther to the east and across the Schnalstal (Figure 2).

On the other hand, it is clear that the displacement along the Schlinig thrust must be taken up by some form of more diffuse straining in the absence of an identifiable intracrystalline shear zone east of the Schnalstal. An estimate for a minimum displacement of 45 km is obtained by measuring the distance in an E-W direction between (1) the easternmost occurrence of Permo-Triassic slivers west of the Schnalstal (Figure 2), which are the remnants of the sedimentary cover of the footwall, and (2) the westernmost erosional relics of the Ötztal basement overriding the Engadine Dolomites (Figure 1).

Previous workers [Helbig and Schmidt, 1978; van Gool et al., 1987] carried out a structural analysis within the area east of Schnalstal where a lithologically distinct series of marble-bearing metasediments (the Schneeberg-Laas series) of presumably Paleozoic age [Hoinkes et al., 1987] can be mapped out as a subunit of the Ötztal basement (Figure 2). A last folding event (locally known as f3 and considered to be of pre-Alpine age by previous workers) produced a pair of spectacular kilometer-scale reclined folds (Figure 11a, axial traces indicated in Figures 2 and 4) with steeply NE dipping fold axes (referred to as "Schlingen" in the German-speaking literature).

Searching for a possible extension of Alpine deformations farther to the east, a structural traverse was undertaken in this easternmost area (upper Zieltal) through a large granodiorite body (Tschigott granodiorite) and into the southern termination of the Schneeberg-Laas series (Figures 2 and 11).

The flow resistant Tschigott granodiorite exhibits a weakly developed foliation, occasionally associated with conjugate shear zones indicating E-W extension. Toward the NW, strain intensity increases. At the same time the foliation swings from an E-W into a NE-SW strike and into paral-

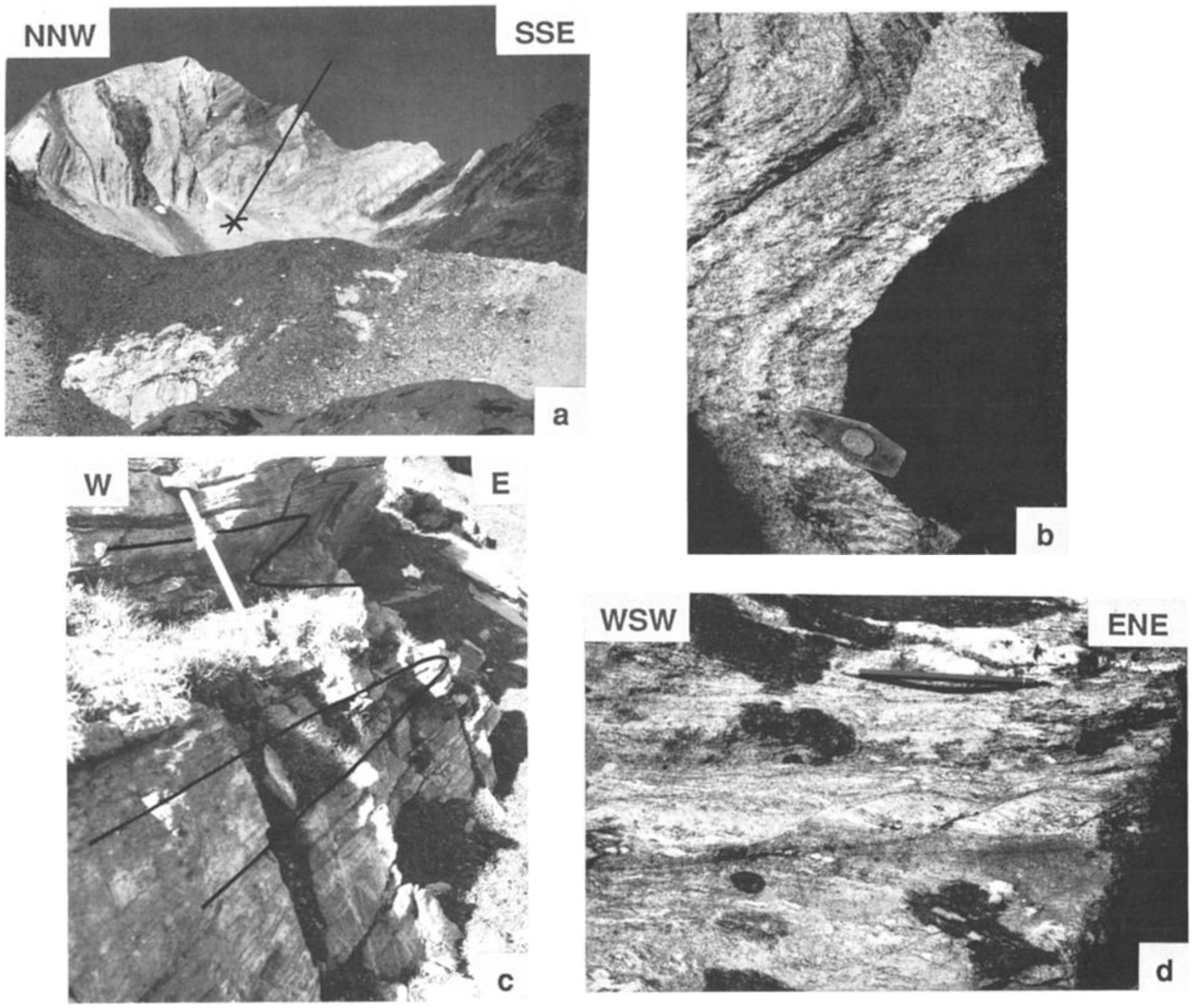

Fig. 11. Alpine deformation east of the Schnalstal. The intensity of Cretaceous deformation increases as the mylonitic rim of the Tschigott granodiorite is approached toward the SE. (a) The marbles of the Schneeberg-Laas series have been isoclinally folded in pre-Alpine times and are now bent into an open kilometer-scale f3 reclined fold of Alpine age (axial plane of f3 indicated, fold axis steeply NNW dipping). Locality is Hohe Weisse, uppermost Zieltal. (b) Typical aspect of f3 crenulation folds in micaschists with weakly developed axial planar schistosity. (c) Isoclinal f3 fold in quartzites, typical for a highly strained region in the vicinity of the mylonitic contact with the flow resistant Tschigott granodiorite. The crenulation folds (Figure 11b) can be continuously traced into these isoclinal folds which therefore are contemporaneous. (d) Shear bands within the mylonites at the NW rim of the Tschigott granodiorite indicating top to the WSW shearing. Mylonitization is contemporaneous with f3 folding.

lelism with mylonites observed to delineate the NW rim of the Tschigott granodiorite body (Figures 11d and 12). These mylonites dip 45° to the NW (Figures 9e and 12). This strain gradient suggests a shearing strain path. Top to the west or NW shearing is indicated by (1) the curvature of the foliation within the Tschigott granodiorite into parallelism with the mylonitized rim (Figure 9e), (2) shear bands within these mylonites (Figures 9e and 11d), and (3) the texture as well as the oblique grain-shaped fabric of quartz mylonite (see Figures 8h and 10d).

Farther to the NW a tight east-closing reclined large-scale f3 fold is followed by a more open west-closing f3 fold (Figures 2, 11a, and 12). Strain intensity during f3 very rapidly decreases to the NW. While a strong axial planar schistosity characterizes small-scale isoclinal f3 folds near the mylonitic contact with the Tschigott granodiorite (Figure 11c), a gradual transition into open crenulation folds is observed farther to the NW (Figure 11b). Finally, these open folds no longer exhibit an axial planar schistosity (Figure 11a). With de-

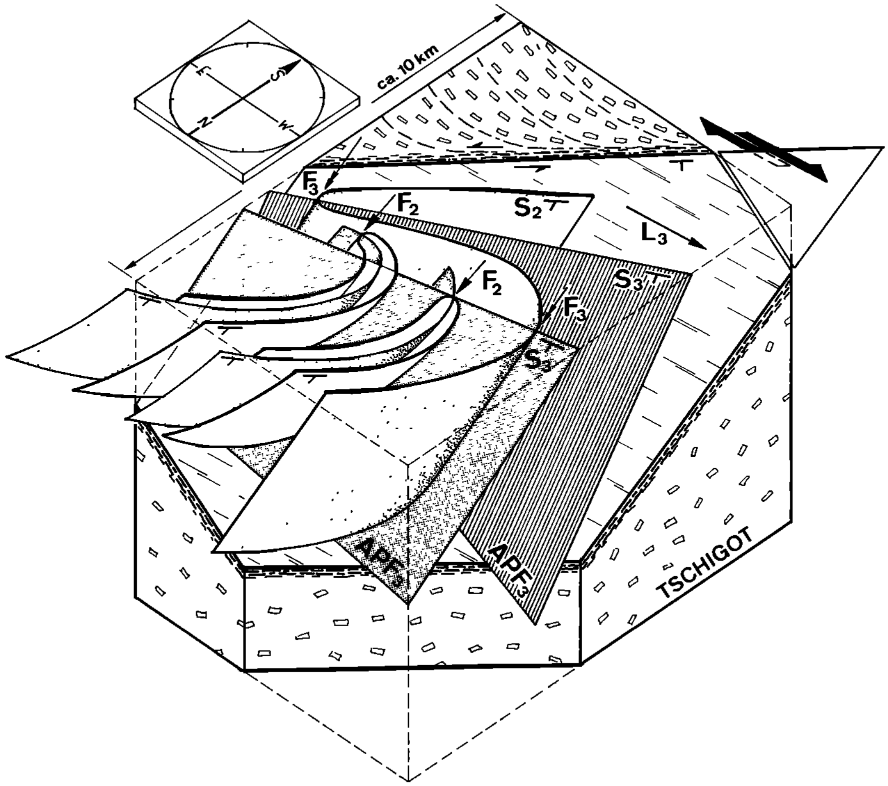

Fig. 12. Three-dimensional sketch illustrating geometry and kinematics (f3 folding and mylonitization) of Cretaceous deformation at the eastern termination of the intrabasement shear zone. For graphical reasons the viewing direction is toward the SE. Cretaceous f3 folding (F3, fold axis; APF3 and S3, axial plane and related schistosity) overprints two large-scale pre-Alpine f2 folds (F2) and the major schistosity (S2) related to the pre-Alpine event. The two f2 closures correspond to the southern termination of the marble horizons in the Schneeberg-Laas series mapped out in Figure 2. L3 indicates stretching lineation and transport direction within the mylonite horizon, which is contemporaneous with f3 folding.

creasing strain intensity the strike of the axial planes fans from a NE-SW strike through an E-W strike into a NW-SE strike (Figures 9f and 12). This strain gradient suggests contemporaneity of f3 folding and mylonitization at the rim of the rigid Tschigott granodiorite. This interpretation is kinematically supported by the determination of the transport direction associated with these f3 folds. Following a method proposed by Ramsay [1967], the orientations of an earlier lineation were measured around f3 folds which exhibit the geometry of a similar fold. A WNW directed transport direction was then inferred from the orientation of the great circle distribution of these lineations (Figure 9e).

Contrary to previous workers, we regard the described large-scale f3 folding to be Alpine in age and related to the Schlinig thrust. All the kinematic indicators summarized in Figure 9e give results which are consistent with the kinematics of the Schlinig thrust. Another very important argument is based on the quartz microstructure found within the quartz mylonite depicted in Figure 8h. If Cretaceous amphibolite grade metamorphism would have overprinted earlier (pre-Alpine) mylonitization, a typical equilibrium grain shape (foam structure) would be expected. Instead, one observes a dynamic (i.e., syntectonic) microstructure indicative for grain boundary migration recrystallization leading to the typical conjugate grain boundary alignments described by Lister and Snoke [1984, Figure 3c]. In the case of quartz this recrystallization mechanism is characteristic for deformation during amphibolite grade conditions.

We conclude that the displacement of at least 45 km along the discrete frontal thrust plane and the intrabasement shear zone is transformed into more diffuse straining associated with folding. The sketch given in Figure 12 summarizes the geometry of this transformation into large-scale f3 folding during top to the west shearing. Local strain concentration led to the mylonitic contact at the NW rim of the Tschigott granodiorite. Kinematic indicators and geometry are compatible with top to the west shearing inferred for the intrabasement shear zone farther to the west.

The Schlinig thrust and its southeastern continuation must have been affected by later deformations. The interference with the Engadine Line was discussed earlier. South of the Engadine Line the strike of the frontal parts of the Schlinig thrust changes from N-S to NW-SE (Figure 2). Within the EW striking intrabasement shear zone of the Vinschgauer Sonnenberge the dip angle increases from 20° to 30° from west to east (Figures 9a and 9c). Finally, the dip increases to the value of 45° for the SW-NE striking mylonites at the NW rim of the Tschigott granodiorite (Figures 4 and 9e). Thus the Ötztal thrust sheet now appears as a large open synclinorium in an E-W profile (Figure 13). Pre-Alpine radiometric ages east of the Jaufen Line [Del Moro et al., 1982] suggest a vertical component of backthrusting, as suggested in the profile of Figure 13, which lead to the rapid cooling during the Late Cretaceous, inferred from radiometric dating by Thöni [1986].

5. INTERACTIONS OF METAMORPHISM AND THRUSTING

5.1. *Cretaceous Mineral Zones*

Variscan amphibolite grade metamorphism (550°-600°C, 5-6 kbar, [Hoinkes et al., 1982]) was overprinted by Cretaceous metamorphism. NE-SW trending mineral zones with increasing metamorphic grade from lowest greenschist facies in the NW to upper amphibolite facies in the SE are well established for this Cretaceous metamorphism in the Ötztal unit [Purtscheller et al., 1987]. Cretaceous climax conditions in the SE are estimated at 600°C and 6 kbar [Thöni and Hoinkes, 1987]. Our own data from the intrabasement shear zone and the adjacent Campo basement enabled us to trace these mineral zones across the eastern continuation of the Schlinig thrust and into the Campo basement (Figure 4).

The metamorphic conditions within the intrabasement shear zone confirm the trend of increasing temperatures toward the east. Near Schleis, the easternmost point where a discrete thrust plane can be observed, the temperatures of metamorphism can only be roughly estimated to be around 250°-300°C (incipient growth of phengite). Therefore the transition into the intrabasement shear zone is expected to occur at around 300°C. Near Eyrs, new growth of phengitic muscovite (6.5 Si per Formula Unit, calculated on the basis of 22 O), chlorite, zoisite, and albite ± biotite within the Permo-Mesozoic indicate temperatures around 400°C [Winkler, 1979].

Near Schlanders, chemically single-zoned garnets appear within the Permo-Mesozoic slivers. They all show a continuous bell-shaped zonation pattern (Figure 14c) typical for garnets grown under an increasing temperature regime (transition greenschist to amphibolite facies) during a single prograde metamorphic event [Tracy, 1982, and references therein]. Within each thin section several of the largest garnets were analyzed in order to ensure that the absence of a double zonation is not due to cut effects. In the Variscan basement, however, we observed double-zoned garnet with a core of garnet 1 and a chemically distinct rim of garnet

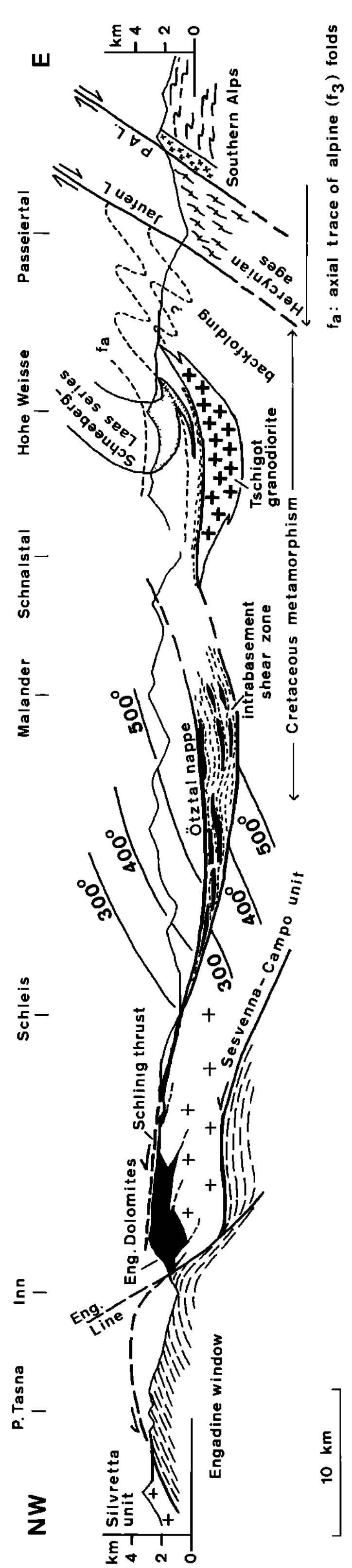

Fig. 13. E-W profile through the Schlinig thrust zone along the trace indicated in Figure 1. P.A.L., Periadriatic fault.

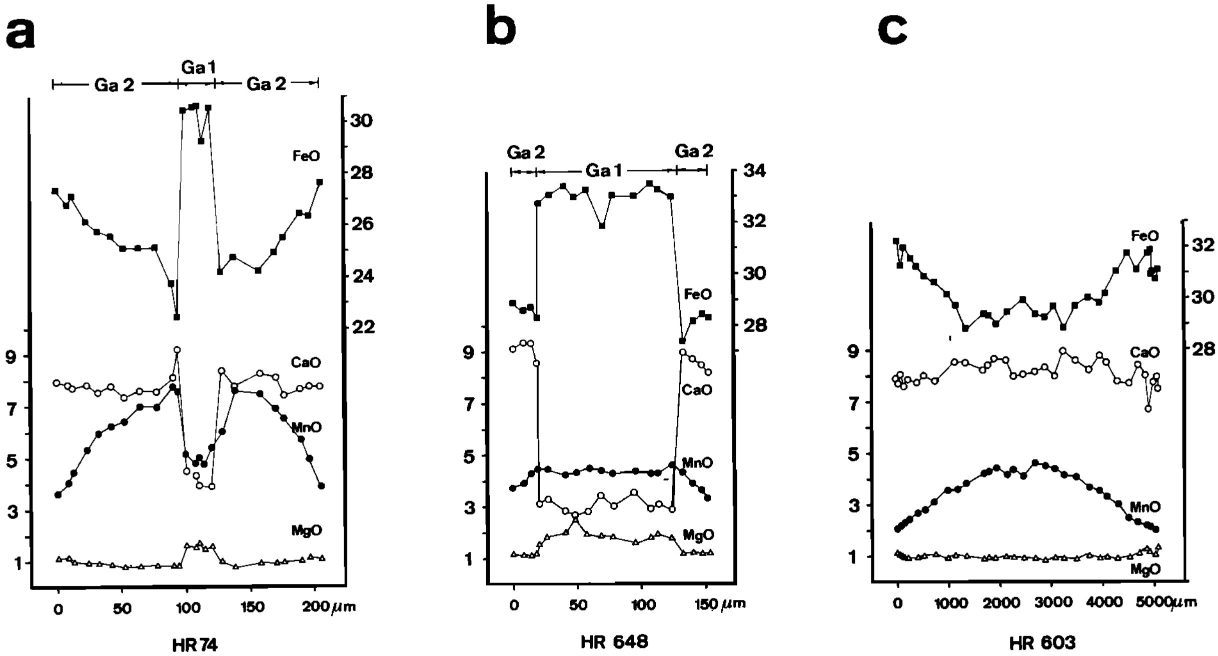

Fig. 14. Chemical zoning profiles of garnet from micaschists in (a) the Ötztal basement north of Schlanders, (b) the Campo basement SE of Schlanders, and (c) inferred Permo-Mesozoic from within the intrabasement shear zone near Schlanders. Profiles of Figures 14a and 14b represent high-temperature cores of Variscan garnet 1, surrounded by a rim of lower-temperature Cretaceous garnet 2. Profile of Figure 14c represents Cretaceous garnet 2 only. Note the bell-shaped zonation pattern of garnet 2, indicating growth during increasing temperature.

2. Cretaceous garnet 2 is restricted to the area east of the mineral zone boundary 2 depicted in Figure 4 and becomes predominant over garnet 1 toward the east. The garnet 1 core exhibits a homogeneous element distribution indicating upper amphibolite facies conditions [Woodsworth, 1977; Yardley, 1977], whereas garnet 2 shows the same element pattern as the garnets of the Permo-Mesozoic slivers (Figure 14). We therefore interpret the single-zoned garnets as the product of Cretaceous metamorphism alone. These chemical data support the view that the intrabasement shear zone also contains Permo-Mesozoic slivers in the region around Schlanders.

An E-W traverse in the northern Campo basement south of the Vinschgau valley largely confirms the same trend toward higher temperatures in the east during Cretaceous metamorphism. In the west chloritoid and sericite are found as pseudomorphs after Variscan staurolite. However, the exact position of the chloritoid-in boundary cannot be located because of the lack of suitable lithologies. The western border of garnet 2 rims around older garnet 1 is well constrained (Figure 4). Farther to the east the thickness of the garnet 2 rims increases steadily. A second staurolite generation, in stable coexistence with chloritoid, replaces Variscan staurolites farther to the east (Figure 4).

Thus in map view an offset of approximately 5-8 km is indicated for the mineral zone patterns depicted in Figure 4. A comparison of about 300 thin sections from within the 2-km-thick intrabasement shear zone yielded no evidence for a major vertical gradient of metamorphic conditions. Judging from the trace of the mineral zone boundary 2 (Figure 4), a local inversion of metamorphic grade within the intrabasement shear zone could be expected.

The dip of the isograds within the Campo and Ötztal basements cannot be directly inferred from field data. Nevertheless, we made an attempt to map out the estimated maximum temperatures in the cross section of Figure 13. The temperature estimates are based on the following calibrations. The first appearance of Cretaceous chloritoid replacing Variscan staurolite north of the Schlinig thrust coincides with the simultaneous reaction musc + bio = kfsp + chl (whole rock Mg/Fe ratio 0.56). For the experimental reaction kfsp + chl = musc + bio + qtz + water, 425°C/4kbar are indicated in the K_2O-FeO-Al_2O_3-SiO_2-H_2O system (475°C/4kbar in the K_2O-MgO-Al_2O_3-SiO_2-H_2O system, respectively) from the work of Hoschek [1973]. Therefore we infer conditions around 440°C/4kbar for the chloritoid-in boundary. Garnet 2 biotite thermometers yield temperatures around 480°C for the first appearance of garnet 2 (corrected after Goldman and Albee [1977] and Matthews et al. [1983]). Farther to the east temperatures inferred from garnet 2 biotite thermometry increase toward about 570°C for the Schnalstal [Haas, 1985] and up to 600°C in the region around the SW termination of the Schneeberg-Laas series [Purtscheller et al., 1987]. For a geotherm of 30°C/km these temperature estimates lead to an apparent dip of 30° to the west (Figure 13). Since the geotherm is unlikely to be greater in a thrusting environment, this apparent dip angle represents a minimum estimate.

The eastern continuation of the Schlinig thrust offsets mineral zones and estimated maximum temperatures by less than 10 km. This is only a small fraction of the minimum total displacement of 45 km. This could indicate either (1) a postmetamorphic reactivation of the Schlinig thrust after complete reequilibration of the isotherms, or (2) continuous but incomplete reequilibration of a disturbed geothermal gradient during thrusting. The first explanation would imply that metamorphism essentially postdates thrusting. This is in conflict with strong evidence for increasing temperatures toward the east during thrusting, provided by structural arguments presented in an earlier chapter. When considering the pattern of isotherms depicted in Figure 13, it is important to realize that the isotherms do not necessarily indicate the maximum temperatures at a given instant of time. In a thrusting environment we would expect continuous heat transfer from the hanging wall to the footwall, as shown by recent modeling [Shi and Wang, 1987]. Continuous reequilibration of isotherms conflicts with earlier models which consider an instantaneous offset of isotherms which relax after thrusting [Oxburg and Turcotte, 1974].

In summary, our findings strongly suggest that metamorphism and thrusting are largely contemporaneous and that reequilibration must occur during thrusting. This view will be substantiated by geochronological evidence given in the next section.

5.2. *Geochronological Evidence*

In this chapter we review and discuss the results of recent K-Ar and Rb-Sr age dating. The original data are published by Thöni [1980a, b, 1981, 1983, 1986] and Thöni and Hoinkes [1987].

Figure 4 shows some of the most significant data gained from fine fractions (K-Ar) and thin slab isochrons (Rb-Sr) on mylonitized rocks from the Schlinig thrust and its continuation into the intrabasement shear zone. These rocks exhibit essentially synkinematically recrystallized parageneses. Nearly all data are within the time bracket 70-100 Ma. A slight lowering of the age values toward the east might be gathered, but this trend can hardly be regarded as significant.

Figure 4 also incorporates the ranges of Cretaceous ages obtained in the area west of the Schlinig thrust, that is, from the sediments of the Scharl Unterbau (98-74 Ma). The mean for 22 K-Ar ages on white mica-rich fine fractions (<2 mm) from the Permoscythian in Val Müstair and the Jaggl window lies at 89 ± 5 Ma. As these micas stem from parageneses with moderate deformation, they are interpreted to reflect primarily the timing of the Cretaceous metamorphism rather than a distinct deformation event. In this area the metamorphic temperatures did not exceed 350°C, the closing temperature of the K-Ar system in white mica. Hence these ages are formation rather than cooling ages. Individual values up to 74 Ma are interpreted to trace slight argon loss due to continuing recrystallization and/or ongoing deformation during cooling.

Farther constraints for a temperature climax at around 90 Ma are provided by (1) a well-defined $^{40}Ar/^{39}Ar$ plateau age of 90 ±1 Ma on a fine fraction from Val Müstair [Thöni and Miller, 1987], and (2) four K-Ar whole rock ages from Verrucano sediments (104-97 Ma) which contain detrital components. These latter model ages are therefore interpreted to represent nearly but not completely reset ages. They provide an upper age limit for Cretaceous metamorphism.

Finally, there is a coincidence of the metamorphic ages from the sediments of the Scharl Unterbau with those from the staurolite-kyanite zone east of the Schnalstal. Here K-Ar and Rb-Sr ages on biotite, $^{40}Ar/^{39}Ar$ ages on white micas, Rb-Sr ages on white micas, and thin slab isochrons on nonmylonitic basement rocks again range between 73 and 100 Ma [Thöni and Hoinkes, 1987].

Combining all this evidence, we conclude that the ages obtained from the mylonitic rocks must be deformation ages. These ages very closely coincide with the ages obtained for the climax of Cretaceous metamorphism in the Scharl Unterbau. Since some of the ages obtained in the high-grade region have to be interpreted as cooling ages, synmetamorphic thrusting at around 90 Ma must have been followed by relatively rapid cooling before 70 Ma.

Because of the age jump from Cretaceous to pre-Alpine ages across the Jaufen fault mentioned earlier, we speculatively interpret this cooling as a consequence of Late Cretaceous backthrusting and backfolding on and in the vicinity of the Jaufen fault. This fault is immediately to the NW of the Periadriatic fault system (P.A.L. in Figure 13) for which a similar scenario of cooling and backthrusting is well documented in the Late Tertiary [Schmid et al., 1989] and in regard to Tertiary metamorphism farther to the west (Lepontine) and east (Tauern).

6. DISCUSSION AND CONCLUSIONS

Thrusting along the Schlinig thrust over a minimum distance of 45 km occurred at around 90 Ma and was contemporaneous with metamorphism. The presence of Cenomanian (97.5-91 Ma) and possibly Turonian (91-88.5 Ma) sediments at the western margin of the Engadine Dolomites [Caron et al., 1982] indicates that this thrusting and metamorphism may even be partly contemporaneous with sedimentation in the west (time scale after Palmer [1983]). The presence of these young sediments near the front of the Schlinig thrust independently confirms the conclusion that thrusting cannot have predated metamorphism.

We connect this extremely rapid transition from sedimentation to thrusting associated with metamorphism to Cretaceous collision of the Austroalpine crust (Apulian plate), with parts of the European foreland now exposed in the Tauern window (Matrei Zone) and along the Arosa suture zone. Frisch [1978] estimates the age of collision in the Tauern window at around 80 Ma, while Ring et al. [1988] document the initiation of west directed thrusting in the Arosa suture zone at around 110 Ma. The counterclockwise rotation of the Apulian plate from about 135 to 65 Ma [Dercourt et al., 1986; Gealey, 1988] implies west directed motion at its northern margin. Ratschbacher [1986] showed that this west directed motion lead to dextral transpression within the entire Eastern Alps during the Cretaceous. At the same time the Helminthoid Flysch of the Western Alps indicates that the closure of the Piemont-Ligurian ocean of the Western Alps is still in progress but not yet achieved [Homewood 1983; Tricart 1984]. It is important to note that the west directed motion in the Tauern window reported by Selverstone [1988] is considerably younger in age (50-15 Ma) and therefore kinematically unrelated to the Schlinig thrust.

The question concerning the heat source responsible for this extremely rapid metamorphism, however, remains a major problem. Frank [1987] suggested that increased heat flow associated with crustal thinning in the Jurassic may provide such an additional heat source. In view of the large time span between crustal thinning and collision (about 80 Ma) this factor is unlikely to play a major role. Thermal modeling of a similar scenario of rapid metamorphism in southern Alaska [James et al., 1989] showed that subduction of very young oceanic lithosphere provides a powerful heat source. In the case of the Eastern Alps, subduction of young Penninic oceanic crust could indeed lead to a very high thermal gradient before the onset of collision.

The pressure estimates of around 6 kbar in the Southern Ötztal unit make it obvious that collision was associated with substantial crustal thickening, although this newly created overburden cannot be held responsible for a rapid increase in temperature. What evidence is there for such a stack of higher thrust sheets above the Ötztal basement? Viewed in a N-S cross section, the Northern Calcareous Alps are the only candidates for such a higher unit. However, this additional overburden is insufficient to produce the peak metamorphic conditions in the southern Ötztal basement, and Frank [1987] provided convincing evidence of more northerly orginal position for this sedimentary unit, which eliminates this possibility altogether.

In view of the structural evidence for west directed thrusting and the existence of even older deformations east of the Tauern window [Frank, 1987] it is more reasonable to postulate stacking of basement units during dextral transpression in the Late Cretaceous, with a progression of deformation from east to west, as proposed by Ratschbacher [1986]. The changeover into north directed stacking occurred substantially later and during the Tertiary [Ring et al., 1988]. Tertiary thrusting led to the final closure of the Tauern and Engadine windows but did not penetratively overprint the Cretaceous structures.

Returning to the Schlinig thrust, we conclude that near-surface thrusting along a discrete thrust plane cannot be uncritically extrapolated to greater depth. At metamorphic temperatures of around 300°C a transition into a wide intracrystalline shear zone is observed. The transformation into large scale-folding at around 500°-600°C indicates that the thrust geometry observed within upper crustal levels cannot be extrapolated into the lower crust.

The deformation of sediments in the footwall of the Schlinig thrust may locally lead to very substantial amounts of stretching due to the extrusion of sediments between rigid basement units. A similar mechanism of extrusion may have been responsible for the detachment of other sedimentary nappes such as the Northern Calcarous Alps or the Helvetic nappes.

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