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Synsedimentary and synorogenic normal faults within a thrust sheet of the Eastern Alps (Ortler zone, Graubünden, Switzerland)

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ABSTRACT

Synsedimentary normal faults of Early Jurassic age and Alpine normal faults of probable Cretaceous age occur together within Triassic sediments of the Ortler zone. The two sets of normal faults have different orientations. The Liassic faults can be identified due to the presence of synrift sediments containing fault-related redeposited sediments. Within the prerift sediments, the Liassic faults acted as rotational planar normal faults bounding tilted blocks. They accommodated substantial stretching (β between 1.3 and 1.65) of the upper crust during the formation of the southern passive margin of the Ligurian-Piemont Ocean.

The Alpine normal faults only affect the Upper Triassic Hauptdolomit. These extensional faults formed simultaneously with Alpine thrusting, as a result of the different lithological properties of the Hauptdolomit and the over- and underlying, less competent rocks. Dolomite cataclasites from Liassic and Alpine fault planes show different microstructures. The Liassic cataclasites were strongly indurated by diagenesis and recrystallization before the Alpine deformation. The microstructure of cataclasites can be used for the recognition of synsedimentary faults in areas where no synrift sediments are preserved.

ZUSAMMENFASSUNG

Die Trias-Sedimente der Ortler-Zone werden einerseits von synsedimentären Abschiebungen frühjurassischen Alters, andererseits von – vermutlich kretazischen – alpintektonischen Abschiebungen durchschlagen. Die beiden Bruchscharen sind verschieden orientiert. Liasische Abschiebungen können aufgrund des Vorkommens von an Bruchstufen geschütteten Resedimenten innerhalb der liasischen Syn-Rift-Sedimente identifiziert werden. Innerhalb der Prä-Rift-Sedimente fungierten die liasischen Brüche als rotationale planare Abschiebungen, die gekippte Blöcke begrenzten. Sie ermöglichten eine beträchtliche Streckung (β zwischen 1,3 und 1,65) der Oberkruste während der Entwicklung des südlichen passiven Kontinentalrandes des Ligurisch-Piemontesischen Ozeans.

Die alpintektonischen Abschiebungen sind nur im obertriadischen Hauptdolomit ausgebildet. Diese Extensionsbrüche entstanden während der alpinen Überschiebungstektonik aufgrund der unterschiedlichen lithologischen Eigenschaften des Hauptdolomits einerseits und der über- und unterlagernden, inkompetenteren Gesteine andererseits. Dolomit-Kataklasite von liasischen und alpintektonischen Bruchflächen weisen eine unterschiedliche Mikrostruktur auf. Vor der alpinen Deformation wurden die liasischen Kataklasite durch Diagenese und Rekristallisation sehr stark verfestigt. Mikrostrukturelle Untersuchungen an Kataklasiten eröffnen die Möglichkeit, synsedimentäre Brüche auch da zu identifizieren, wo Syn-Rift-Ablagerungen nicht mehr erhalten sind.

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Introduction

Analysis of former rift and passive continental margin geometries within an orogen like the Alps is difficult in view of the very strong compressional overprint. Alpine folding and thrusting during Cretaceous and Tertiary times have deformed and dismembered the southern continental margin of the Jurassic Tethys Ocean which now lies in the Eastern and Southern Alps. Nevertheless, this margin has a potential to yield very valuable information on the mechanisms of crustal extension, as structural styles of extension at all crustal levels can be studied (including the lower crust in the Ivrea zone).

Ductile extensional deformation in the lower crust of the Southern Alps during the Jurassic was studied by HODGES & FOUNTAIN (1984), HANDY (1986), SCHMID et al. (1987), and BRODIE & RUTTER (1987). From the sedimentology of the Jurassic sediments in the Eastern and Southern Alps, evidence for crustal extension was provided by TRÜMPY (1960), BERNOULLI (1964), CASTELLARIN (1972), WINTERER & BOSELLINI (1983), EBERLI (1985, 1987), and many others. LEMOINE & TRÜMPY (1987) provide a summary of the present state of knowledge in this field. Little is known, however, about the geometry of the fault systems accommodating the extension of the upper crust. One main problem is the distinction between Jurassic paleofaults and Alpine faults, especially Alpine *normal* faults such as those recently described by MANCKTELOW (1985), SELVERSTONE & HODGES (1987) and SCHMID & HAAS (submitted). The following paper reports an example of both synsedimentary and synorogenic brittle normal faults coexisting in Mesozoic sediments of a thrust-sheet in the Austroalpine nappes of Eastern Switzerland. Emphasis is placed on tectonic, sedimentological, and microstructural criteria allowing a distinction between these two types of faults. The geometry of Jurassic extensional faults in the western Ortler zone is reconstructed and the role of Alpine normal faults within the framework of the regional Alpine deformation is discussed.

Regional setting

The Central Austroalpine complex (TRÜMPY 1980) represents a highly allochthonous nappe system consisting of huge pre-Alpine basement units and their Mesozoic sedimentary cover. During the polyphase Alpine deformation in Cretaceous and Tertiary times, these nappes were stacked upon the Lower Austroalpine units, which in turn came to lie upon the ophiolite-bearing Upper Penninic nappes representing remnants of the Jurassic to Cretaceous Tethys ocean (Fig. 1).

The Mesozoic of the Central Austroalpine complex has partly (e.g. the Quattervals unit of the Engadiner Dolomiten) been sheared off from the basement and partly it is still in contact with it, as is the case for part of the Ortler zone representing the sedimentary cover of the Campo crystalline mass (TRÜMPY & HACCARD 1969). The study area lies in the western Ortler zone between the Engadine valley and the Swiss–Italian border. To the north, this part of the Ortler zone is structurally overlain by the Quattervals unit, consisting largely of thick Upper Triassic carbonates. The contact between the Quattervals unit and the Ortler unit is formed by the Quattervals thrust or Trupchun-Braulio line (SCHMID 1973), a NE-dipping, probably SW-directed thrust (TRÜMPY & HACCARD 1969).

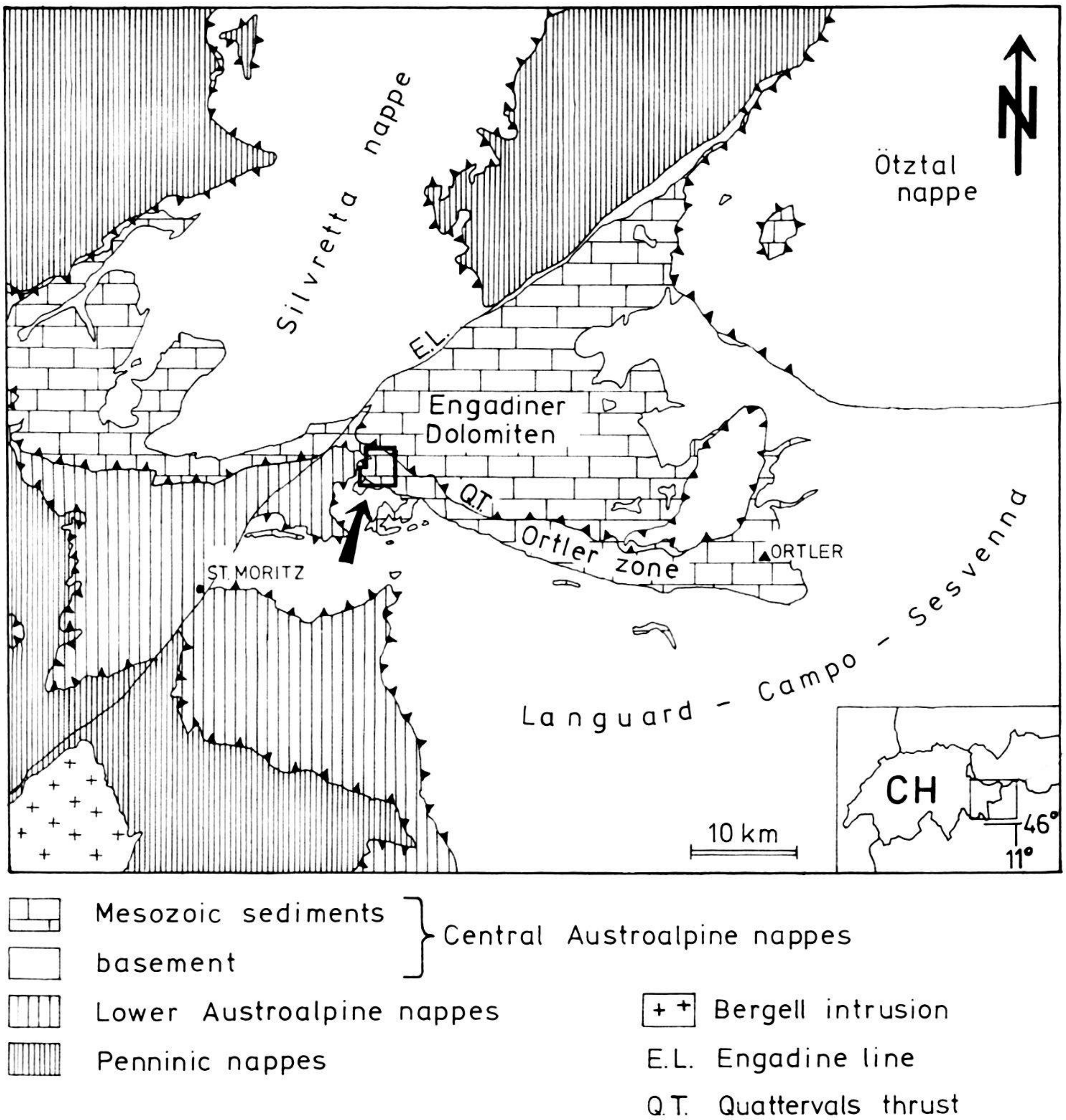


Fig. 1. Tectonic sketch map of eastern Graubünden with parts of Italy and Austria. The Austroalpine nappes represent parts of the southern margin of the Jurassic Tethys Ocean. Ophiolites of this ocean are found in the underlying Penninic nappes. Arrow indicates the study area. After SPICHER (1972), simplified.

At its southwestern border, the Ortler zone is underlain by the Languard unit, which in turn rests on the Lower Austroalpine nappes. Some intermediate tectonic slivers occur between these units.

The Chaschauna, Trupchun and Müschauns valleys expose a complete section across the western Ortler zone, consisting of (from south to north): gneiss of the pre-Alpine basement, a Permo-Triassic continental to shallow-marine sedimentary sequence, and thick Lower Jurassic hemipelagic sediments (Allgäu Beds). Upper Jurassic and Cretaceous sediments occur in a narrow, overturned syncline just below the Quattervals thrust. The Triassic series are strongly reduced in thickness by (1) erosion during the Early Jurassic rifting phase and (2) the occurrence of normal faults. These are partly synsedimentary normal faults of Early Jurassic age and partly Alpine, synorogenic normal faults. While the former can be followed down to the basement, the latter are restricted to the level of the Upper Triassic Hauptdolomit, a monotonous sequence of sub- to supratidal dolomites, which were about 800 to 1000 m thick before extensional faulting. Today the Jurassic normal faults cutting the Hauptdolomit dip towards the northeast, whereas the Alpine ones dip mostly towards the southeast. Jurassic and Alpine faults can be distinguished using the following criteria:

1. Jurassic faults are directly related to the facies pattern in the synrift sediments (Allgäu Beds).
2. Alpine normal faults in the Hauptdolomit are compatible with Alpine deformation in other parts of the sequence.
3. Cataclasites from Jurassic and Alpine faults show different microstructures.

This is confirmed by cross-cutting relationships between the younger (Alpine) and older (Jurassic) faults.

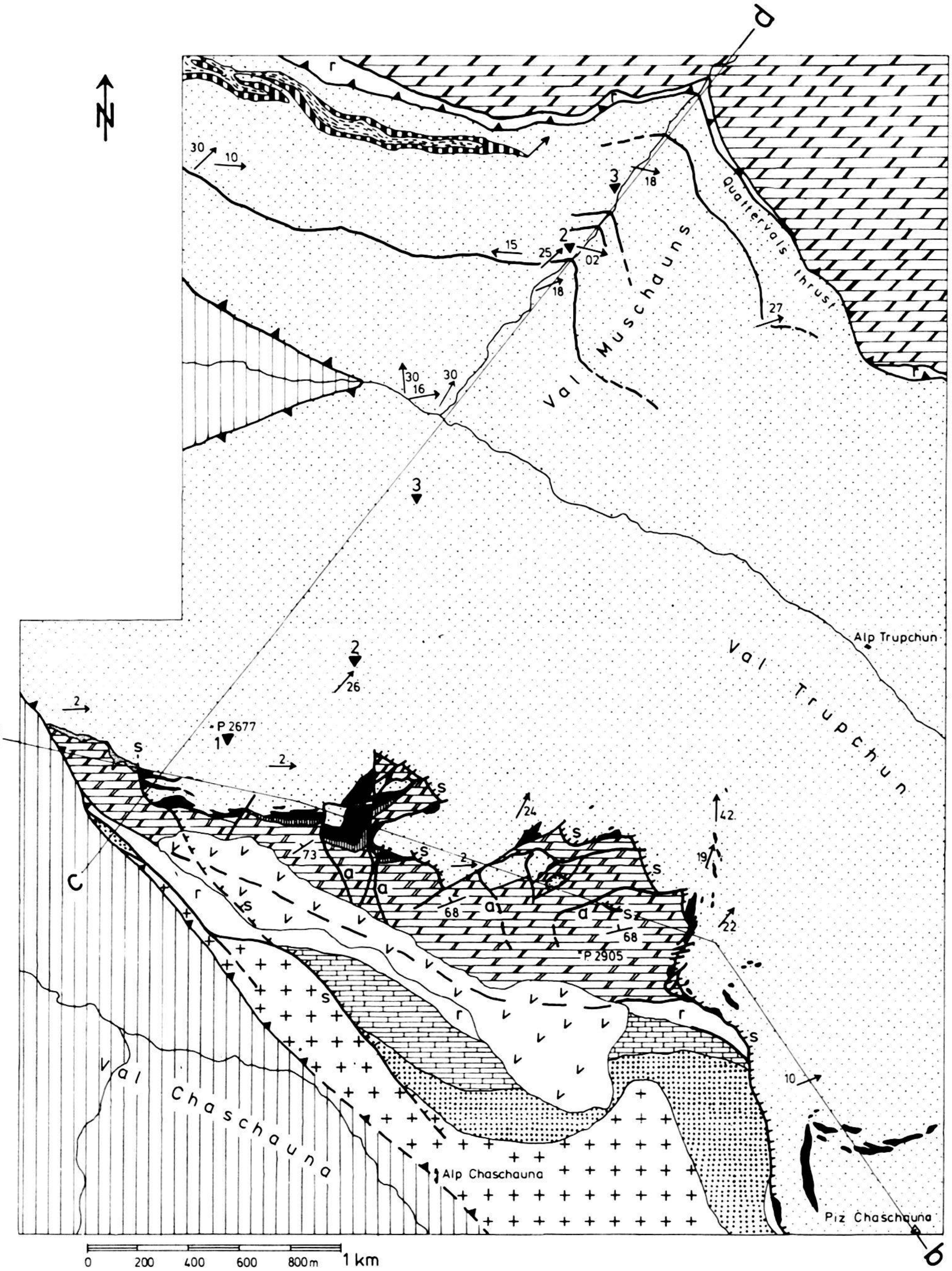
Synsedimentary normal faults

Fault-related sedimentation in the Early Jurassic

The sedimentology of the uppermost Triassic and Lower Jurassic sediments of the Ortler unit was studied by Furrer (1981) and Eberli (1985, 1987). Eberli (1987) developed a facies model relating the different facies associations in the Lower Jurassic Allgäu Beds to the activity of normal faults: Megabreccias, conglomerates and calciturbidites alternating with the "autochthonous"marls and limestones of the Allgäu Beds

Fig. 2. Geological map of the study area.

Hauptdolomit of the Quattervals unit (Norian)
Aptychus Limestone + Couches rouges (Uppermost Jurassic, Cretaceous)
Radiolarite (Upper Jurassic)
Allgäu Formation; black: Chaschauna Breccia (Lower Jurassic)
Alv Breccia (Lower Jurassic)
Kössen Formation (Rhaetian)
Hauptdolomit (Norian)
r Raibl Formation (Carnian)
Middle Triassic carbonates
Permian - Lower Triassic clastics
basement
deeper tectonic units (Lower Austro-alpine, Languard nappe, etc.)
3 Early Pliensbachian ammonites (Eberli 1985)
2 Late Sinemurian " "
1 Early Sinemurian " "
a Alpine normal fault
s Liassic synsedimentary normal fault
23 fold axis with plunge angle
landslide


N
Quattervals thrust
Val Muschauns
Val Trupchun
Alp Trupchun
Val Chaschauna
Alp Chaschauna
Piz Chaschauna
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a
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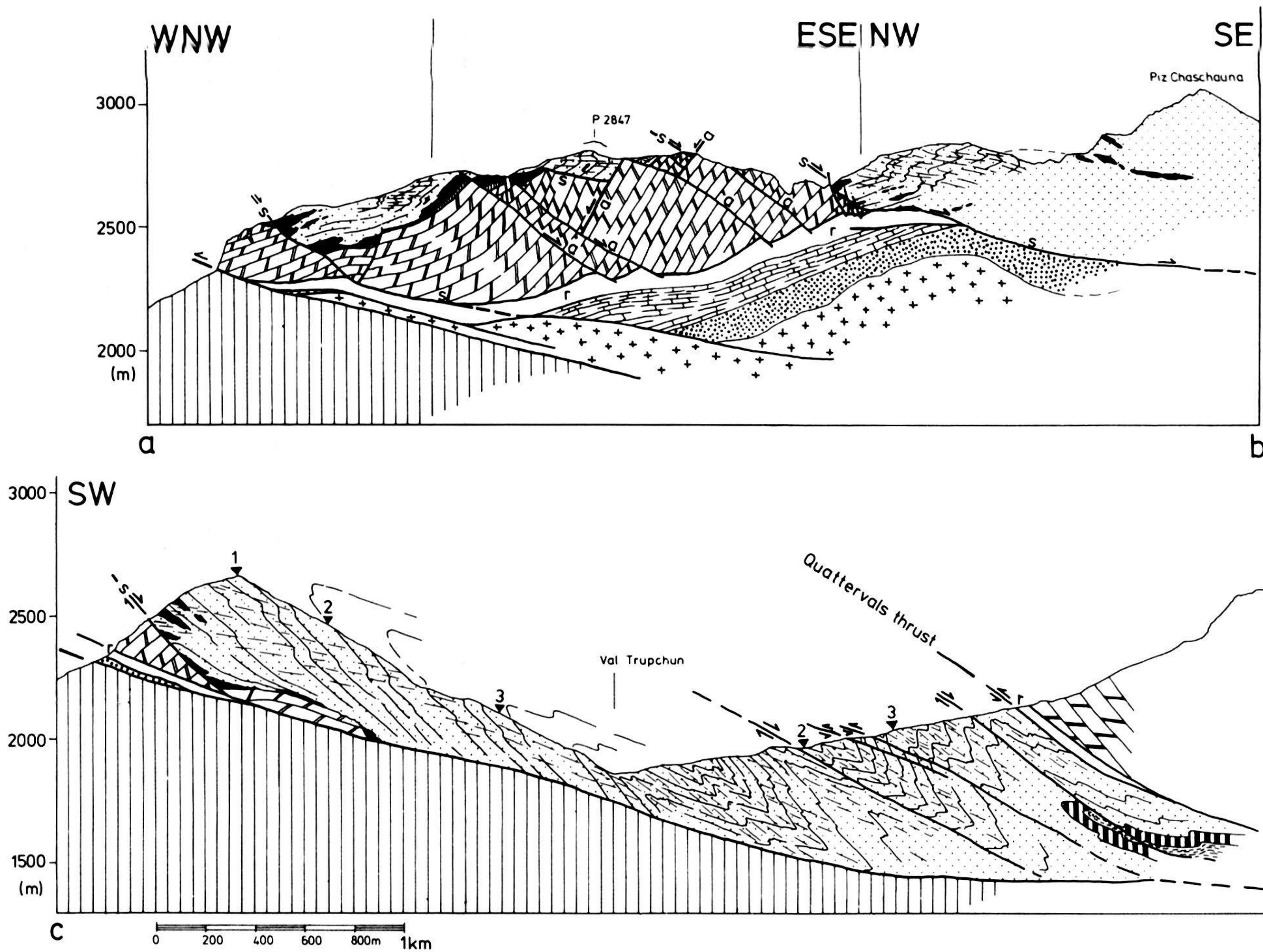


Fig. 3. Geological sections through the study area. Section a–b shows important synsedimentary normal faults (s) with related Jurassic resediments (black). Additionally, Alpine normal faults (a) deform the Hauptdolomit in "domino" or "bookshelf" style. Note that the section is not perpendicular to strike of synsedimentary faults. Section c–d shows overturned folds of the Trupchun Lias. See Figure 2 for legend and location of sections.

were deposited along submarine normal fault scarps bounding asymmetric basins. Mapping of the redeposited sediment bodies by the author allowed to identify these normal fault scarps (see below).

The most spectacular redeposited sediments are chaotic megabreccias (Chaschauna Breccia) exposed near the crest of the mountain ridge between the Chaschauna and Trupchun valleys. These breccia beds are composed of large boulders (up to several meters in diameter) and slabs of Upper Triassic to Lower Jurassic carbonates (Norian Hauptdolomit, Rhetian Kössen Beds, Liassic Alv Breccia) in a dark marly matrix. They occur as a locally developed, more or less continuous, up to 50 m thick layer at the base of the Liassic sequence, or as wedge- or lense-shaped bodies intercalated higher up in the sequence (Fig. 2, Fig. 3). The ratio between Rhetian (Kössen Beds) and Norian (Hauptdolomit) components varies widely, but generally the Kössen clasts dominate in the basal breccia layer and the proportion of Hauptdolomit fragments increases upward in the sequence. The breccia layers near the summit of Piz Chaschauna contain almost exclusively Hauptdolomit components, among them a spectacular, several 100 m long Hauptdolomit slab. The deposition of the Chaschauna Breccia reflects the erosion of the Upper Triassic sequence: the Kössen Beds are only locally preserved and the fossil-rich, massive limestones in the upper part of the Kössen Beds (Zirmenkopf Limestone, FURRER 1981) have been totally removed and are now only found as large boulders within the Chaschauna megabreccia. From sedimentological evidence, EBERLI (1987) postulates transport of the Chaschauna Breccias by debris flow and submarine rockfall from the fault scarps into the basins. In addition to these processes, bedding-plane-parallel gliding and slumping were also active in the formation of the basal Chaschauna Breccia layer. For example, west of P. 2847, the basal breccia develops laterally from broken and dismembered Rhetian carbonate beds alternating with shales. This implies mass transport on the surface of a fault block induced by block tilting in an early stage of fault activity.

In the westernmost part of section a–b (Fig. 3), the Hauptdolomit is overlain by Liassic breccias of the type "Alv Breccia" (SCHÜPBACH 1974) with an angular unconformity. These breccias also fill cavities in the Hauptdolomit. In contrast to the Chaschauna Breccia, they show a reddish to yellow micritic matrix of calcareous to dolomitic composition. Most of the components are clasts of Hauptdolomit. The Alv Breccias are interpreted as having formed in situ, or with minor gravitational transport, on top and at the flanks of submarine highs (FURRER 1985). In this case, they were deposited at the deeply eroded edge of a tilted fault block. A large, redeposited mass of Alv Breccia also occurs within the Chaschauna Breccia in the adjacent basin.

Based on the assumption that the breccias and other redeposited beds are directly related to fault activity, these beds provide information for the timing of synsedimentary faulting. EBERLI (1988) found paleontological evidence that the onset of fault-related sediments in the Ortler unit becomes younger from east (Early Hettangian at il Motto near Livigno) to west (Early Sinemurian in the western part of the Chaschauna section near P. 2452), indicating a westward propagation of faulting.

Geometry of synsedimentary normal faults

In spite of the strong Alpine deformation, the geometric relationships between the Liassic rocks and the underlying prerift sequence have remained relatively undisturbed. Some of the megabreccia bodies within the Liassic sequence are directly connected with two important synsedimentary normal faults cutting the Hauptdolomit (Fig. 3, section a–b). The easterly fault also clearly cuts through Middle and Lower Triassic as well as Permian rocks, while for the westerly one the downward prolongation is somewhat problematic due to bad outcrop conditions. The segments of synsedimentary faults separating Hauptdolomit and Allgäu Beds in the middle part of the section are all parts of the easterly fault offset by Alpine normal faults. The distribution of the megabreccias shows that the fault scarps faced towards the east or northeast. It can be concluded from the different extent of erosion of the prerift sediments between the faults that the fault blocks were tilted in the opposite direction (west or southwest): approaching the faults from the west, the Kössen Beds disappear and Liassic breccias discontinuously overlie the Hauptdolomit.

The segments of the easterly fault can be used for some geometrical considerations. Today they dip towards northeast (Fig. 7d), while stratification in the Hauptdolomit dips at high angles towards NNW. For a reconstruction of the original geometry, Alpine deformation must be considered. The Hauptdolomit has been affected first by Alpine "domino-style" rotational normal faulting and then by tilting of the whole western Ortler zone towards NNE (see below). The effect of NNE-tilting can be eliminated by back rotation towards SSW. This gives a pre-Alpine dip direction of the fault plane towards the east (Fig. 7e). The dip angles are then between 23° and 53°, with an average of 32°. The effect of Alpine "domino"-faulting is difficult to quantify, as this process affected the series already faulted and tilted by Liassic tectonics. It can be assumed, however, that this effect was not too important, because the offset induced by the Alpine normal faults remained relatively small. A 15° rotation of the dominoes – which is a rather high estimate – would have changed the dip of the Jurassic normal fault by 10°, and the reconstructed average pre-Alpine dip of the fault plane would then be 42°. The angles 32° and 42° can thus be taken as minimum and maximum estimates for the pre-Alpine fault dip.

The angles between Hauptdolomit stratification and fault plane measured in the field range from 48° to 76°. The average angle is 61°. A systematic interdependence between this angle and the stratigraphic level within the Hauptdolomit, i.e., a listric shape of the fault plane, is not observed. The overall planar shape of the fault – as far as it is exposed – is also clearly visible in Figure 4. According to WERNICKE & BURCHFIEL'S (1982) classification, the fault is of the rotational planar type: it was initiated with a dip angle of about 61° and rotated during its activity to its final dip of about 32° (42°). Under the assumption that extension of the prerift sediments was accommodated by ideal rotational planar faults (domino mechanism), the extension ratio β can be estimated using the simple formula given by JACKSON & MCKENZIE (1983):

$$\beta = \sin\theta / \sin\theta',$$

where θ is the initial fault dip and θ' the final fault dip. If the final fault dip is assumed to be 32°, the resulting extension ratio is 1.65. If the more conservative estimate of a 42° final fault dip is chosen, an extension ratio of 1.3 results. The true value probably lies between these two numbers.

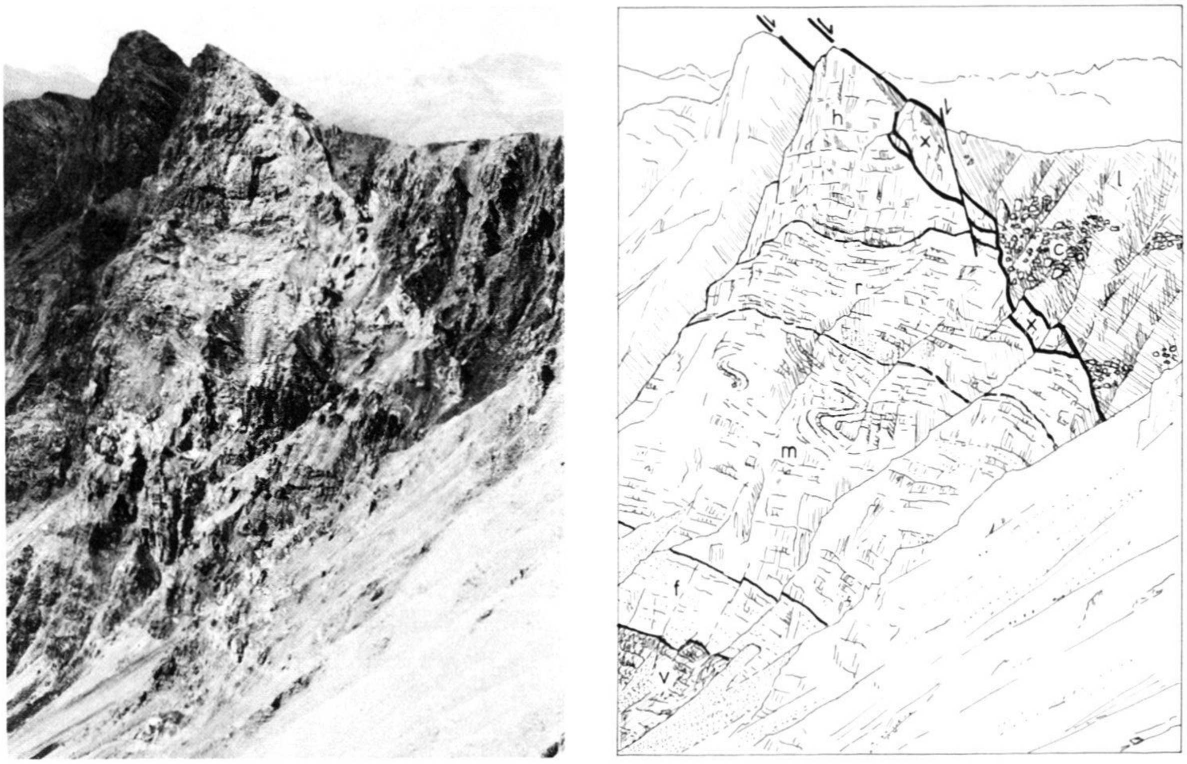


Fig. 4. Liassic synsedimentary normal fault. (v, f): Verrucano and Fuorn Formation (Permian to Lower Triassic clastics); (m): Middle Triassic carbonates; (r): Raibl Beds; (h): Hauptdolomit; (l): Allgäu Beds, (c): Chaschauna Breccia. (x) indicates slabs of Hauptdolomit displaced along the fault plane. The Liassic fault is cut by a small Alpine normal fault. Northeast is to the right. Crest between Chaschauna and Trupchun valleys. The left one of the two summits is P. 2905.

This is, of course, only a crude estimate containing several uncertainties. The assumption of ideal rotational planar faults may be an inadequate simplification, as we cannot reconstruct the geometry of the faults deeper down in the basement where they may well become listric. The calculated extension ratio lies, however, in the range of what could be expected by comparison with the data from the Armorican margin published by LE PICHON & SIBUET (1981) and CHENET et al. (1982).

Alpine deformation of Hauptdolomit and Allgäu Beds

The Alpine faults cutting the Hauptdolomit are mostly SE-dipping normal faults. To a minor extent, bedding-plane-parallel, NW-dipping normal faults occur (Fig. 5). The Alpine age of these structures is indicated by (1) the fact that the faults are not associated with megabreccias and (2) their compatibility with Alpine deformation in the overlying Allgäu Beds. The second point will be examined in the following.

In the Allgäu beds of Val Trupchun, Alpine deformation produced open to tight folds with a well-developed axial plane cleavage (Fig. 6). To a minor extent, folds are also observed in the Middle Triassic carbonates below the Hauptdolomit (Fig. 4). The fold axes in the Allgäu beds run N–S to W–E (Fig. 2, Fig. 7a). Although the orientation of the axes varies over such a wide range, no overprinting relationships between individual folds

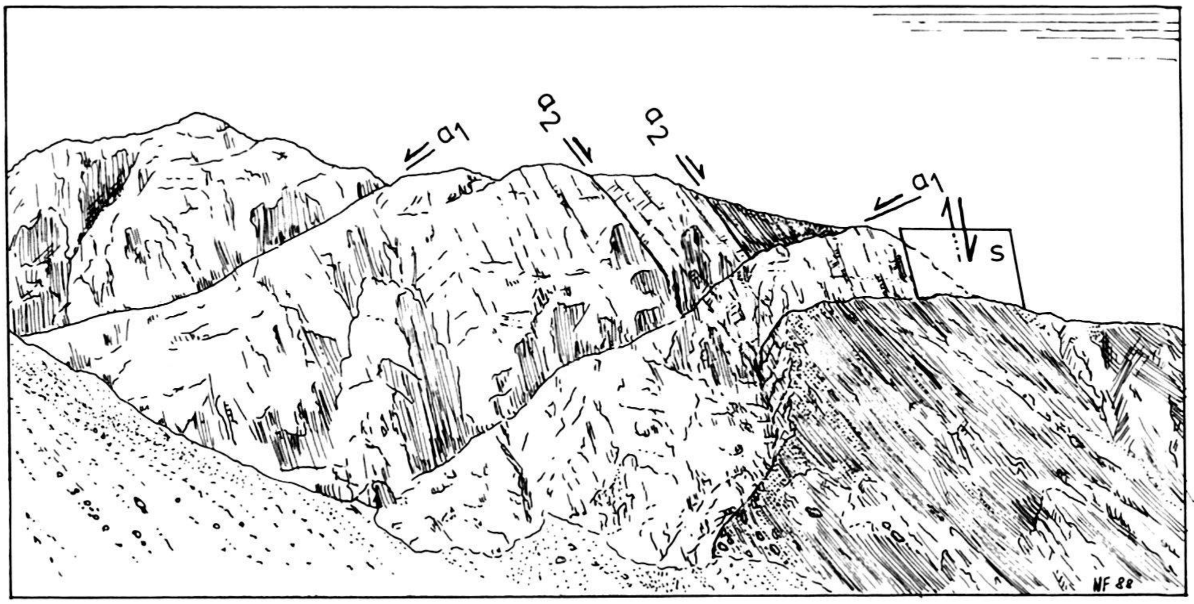


Fig. 5. NE-dipping Liassic normal fault (s), SE-dipping Alpine normal faults (a_1), and NW-dipping, bedding-plane-parallel Alpine normal faults (a_2) cutting Hauptdolomit (light) and Allgäu Beds (dark). Southeast is to the left. Southern side of Val Trupchun, the summit to the left is P. 2905. (After photograph.)

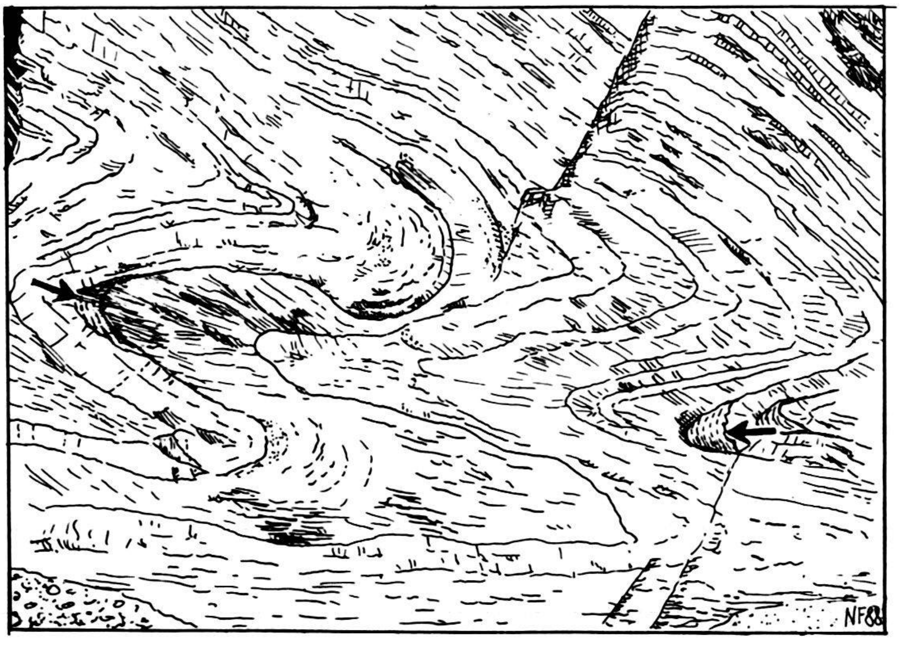


Fig. 6. Tight folds with axial plane cleavage in the Allgäu Beds. Arrows indicate differently oriented fold hinges. Outcrop is about 8 m high, northwest is to the left. Val Trupchun near Purcher. (After photograph.)

are observed and folding of the Trupchun Lias must have developed continuously. Second folding occurs only in the southeast, near the summit of Piz Chaschauna. In the following analysis this area is excluded.

In stereographic representation (Fig. 7a, b), F1 fold axes and s_0–s_1-intersection lineations measured in the Val Trupchun area come to lie on a great circle. The pole to this great circle nearly coincides with the maximum of the poles to cleavage planes, i.e., all fold axes lie roughly within the same axial plane defined by the cleavage. From this observation, it is likely that the present distribution of fold axes is an effect of reorientation of folds during simple shear, with axes that had been initiated perpendicularly or obliquely to the shear direction and then partly rotated towards the shear direction according to the mechanism described by ESCHER & WATTERSON (1974).

After folding, the Liassic sequence together with the underlying Hauptdolomit and deeper Triassic were tilted towards NNE, as can be seen in Figure 3, section c–d: The axial planes of the folds are in an overturned position and the facing direction plunges

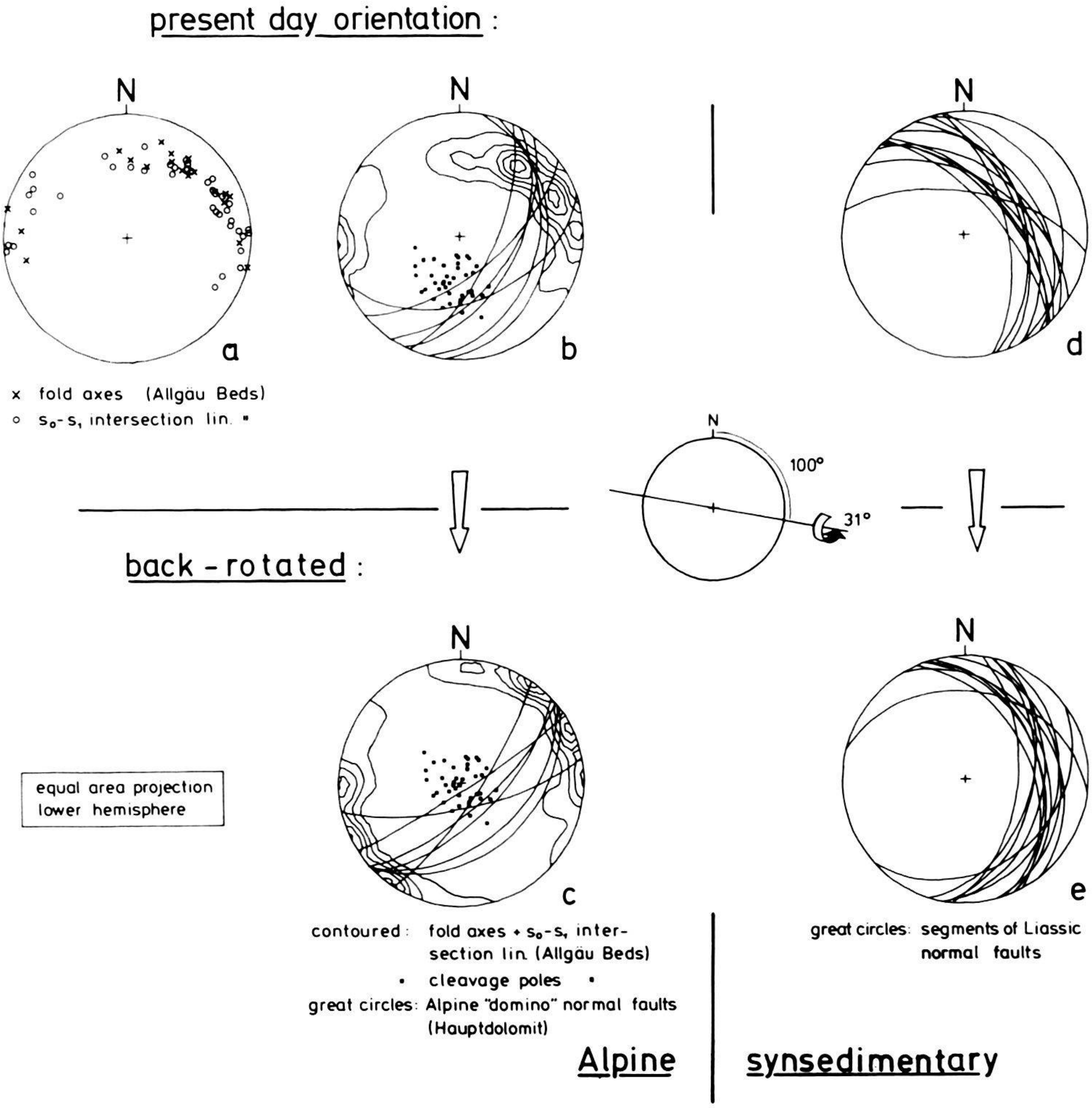


Fig. 7. Stereographic representation of main structural elements in the study area. a: Fold axes and s_0–s_1-intersection lineations in the Allgäu Beds in present day orientation. b: Fold axes and intersection lineations (contoured) in the Allgäu Beds, poles to cleavage (dots) in the Allgäu Beds, and traces of Alpine normal faults in the Hauptdolomit in present day orientation. c: The same as b, after back-rotation towards SSW. d: Traces of segments of Liassic normal fault in present day orientation. e: The same as d, after back-rotation towards SSW. See text for further explanation.

towards north to northwest. In order to restore the situation before tilting, the structural elements have to be rotated back to the SSW at least until cleavage comes into a horizontal position. For this minimum rotation, a horizontal rotation axis striking ESE (100°) and a 31° angle of rotation were chosen. The chosen rotation axis is parallel to the general strike of the Ortler zone. In Figure 7c, this operation has been carried out for the fold axes and intersection lineations in the Allgäu Beds, cleavage in the Allgäu Beds, and the Alpine normal faults of the Hauptdolomit. If the distribution of fold axes is a result of reorientation under simple shear, the shear direction was most probably SE–NW (about 330°), because the reorientation (rotation angle) required for individual fold axes is then at a minimum. This direction is perpendicular to the average strike of the SE-dipping Alpine normal faults (Fig. 7c). This leads to the possible explanation that the different tectonic style of Hauptdolomit and Allgäu Beds was caused by their different mechanical properties: top-to-NW directed shearing of the relatively competent Hauptdolomit was accommodated by SE-dipping, antithetic normal faults according to the "bookshelf" or "domino" mechanism, while, in the relatively incompetent Allgäu Beds, it led to rotation of slightly earlier initiated folds towards the shear direction. The bedding-plane-parallel, NW-dipping normal faults in the Hauptdolomit are conjugate to the SE-dipping ones. They may have functioned as synthetic shear planes in an early stage of deformation, before they were inactivated by progressive rotation of the "dominoes".

A similar situation is reported by SCHMID & HAAS (submitted) from the Northern Engadine Dolomites where SE-dipping Alpine normal faults in the Hauptdolomit are also observed together with folding in the under- and overlying sediments. SCHMID & HAAS relate both folding and faulting to SE–NW directed overthrusting of the Ötztal crystalline complex (Schlinig thrust) during the Late Cretaceous. The compatibility problem arising from the fact that the Hauptdolomit was substantially stretched in a SE–NW direction while the Allgäu beds were folded leads these authors to the assumption of NW-directed "extrusion" of the Hauptdolomit between the footwall and hanging-wall basement blocks of the thrust. This process may also have played a role in the deformation of the western Ortler zone.

It is important to note that the Quattervals thrust is not responsible for folding of the Trupchun Lias: the folds are cut off by this thrust, which is younger and has an apparent transport direction from northeast to southwest (TRÜMPY & HACCARD 1969). We therefore have to assume a higher tectonic unit thrusted from southeast to northwest over the Ortler sediments before the Quattervals thrust was active. Remnants of this inferred unit are not preserved in the Ortler zone, in contrast to the northern Engadine Dolomites, where tectonic klippen of crystalline basement lie on top of the sedimentary sequence. These klippen belong to the Ötztal unit thrusted over the Engadine Dolomites during the Late Cretaceous (SCHMID & HAAS, submitted).

Liassic and Alpine cataclasites

Since Liassic and Alpine faults in the study area can be easily identified using tectonic and sedimentological criteria, the cataclastic rocks from Liassic and Alpine fault planes cutting the Hauptdolomit were examined in order to find diagnostic microstructural characteristics of the two fault types.

The most typical feature of the Liassic cataclasites is their very good subsequent lithification. They are often more resistant against erosion than the "normal" Hauptdolomit and form steep rock faces, defining the fault plane where the hangingwall rocks have been removed by erosion (see Fig. 4). The cataclasites occur in layers of several decimeters thickness parallel to the fault planes. They are observed on fault planes between footwall Hauptdolomit and hangingwall Allgäu beds as well as along faults within the Hauptdolomit. Macroscopically, they consist of carbonate clasts in a dark grey to reddish matrix. Clasts have any size up to 30 cm. A variety of lithologies are found in the cataclasites, all derived either from the Hauptdolomit (sparitic dolomites, recrystallized oolitic dolomites, etc.) or the Kössen Beds (micritic limestones with microfossils). On faults within the Hauptdolomit, no Kössen clasts are found.

In thin sections, the matrix is found to be composed of microscopically- and submicroscopically-sized fragments produced by cataclasis, e.g. idiomorphic dolomite crystals derived from the destruction of sparitic Hauptdolomit clasts (Fig. 8b). The larger clasts are rounded or angular. Figure 8b shows a section through a clast with two straight sides and one rounded side, obviously produced by fracturing of a rounded clast. The first stage of the fracturing process is represented by microfractures observed in some clasts (Fig. 8b). From these microfractures, ultracataclasite-bearing fractures can develop leading to the disintegration of the clast (Fig. 8c). A conspicuous proportion of the clasts consist of reworked, slightly older cataclasite ("secondary clasts", Fig. 8a). A preferred orientation of non-isometric clasts relative to the fault plane is not observed. Sparry calcite or dolomite cements are almost absent in the Liassic cataclasites: all voids are filled with ultracataclastic material. Thin calcite veins observed in many samples cut across clasts and matrix without being offset, indicating an age of the veins younger than formation and induration of the cataclasite (Fig. 8d).

The post-Liassic history of the cataclasites includes diagenetic processes and Alpine deformation. Recrystallisation of the fault rocks often obliterates the cataclasite fabric. Recrystallization starts with single dolomite crystals growing in the matrix but can also affect clast margins and even whole clasts (Fig. 8e). Further post-cataclastic features are the above-mentioned veins and stylolitic seams (Fig. 8d). Where Liassic faults are cut by Alpine ones, Alpine cataclasis can totally destroy the Liassic fabric.

From the mircostructure of the cataclasites, the following assumptions can be made for their formation:

- The Liassic fault rocks were produced by cataclasis. Pressure solution and redeposition were not important as deformation mechanisms, but only in the induration of the cataclasite.
- During fault movement, the size of the clasts was reduced by frictional wear of clast surfaces (leading to rounded clasts) and by fracturing of clasts (leading to angular ones).

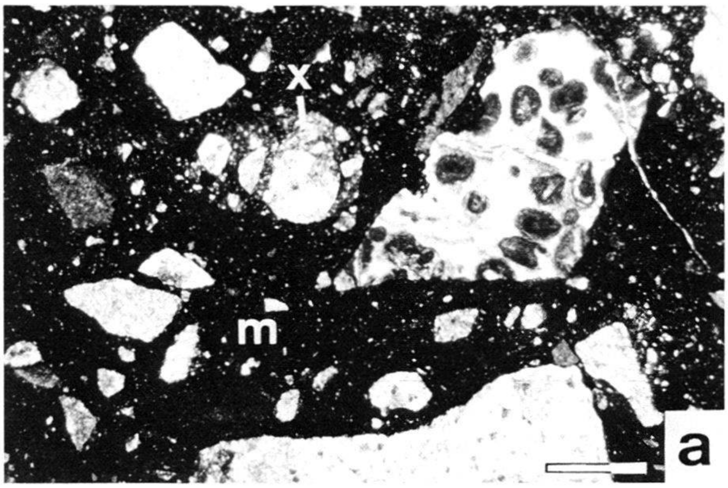
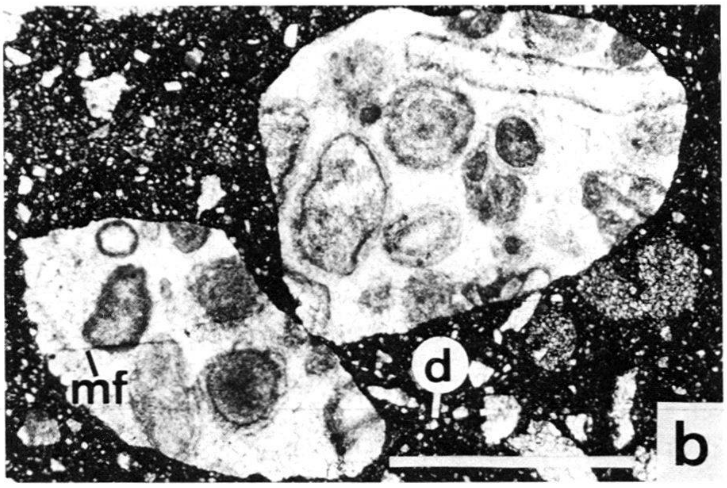
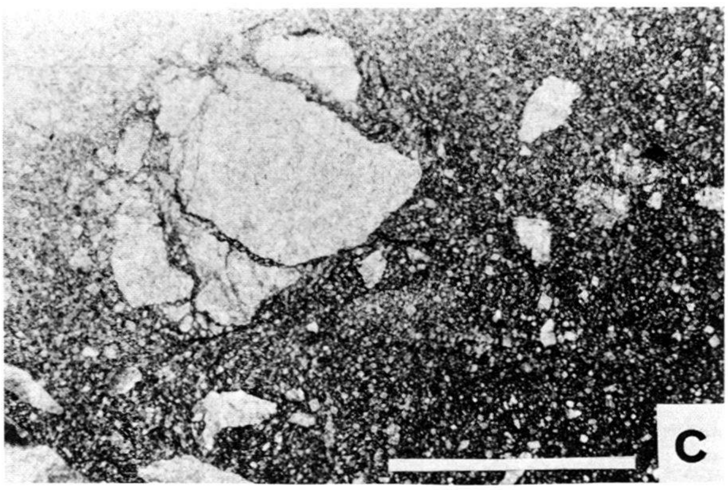


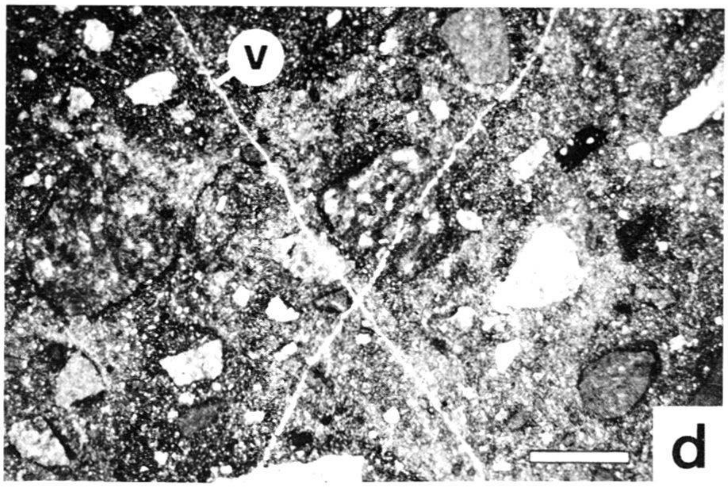
Fig. 8. Photomicrographs of Alpine and Liassic cataclasites from the western Ortler zone. Scale bar is always 1 mm long.
a: Cataclasite from a Liassic fault between Hauptdolomit and Allgäu Beds showing angular clasts in a dark ultracataclasite matrix (m). (x) is a "secondary clast" consisting of reworked, slightly older cataclasite.



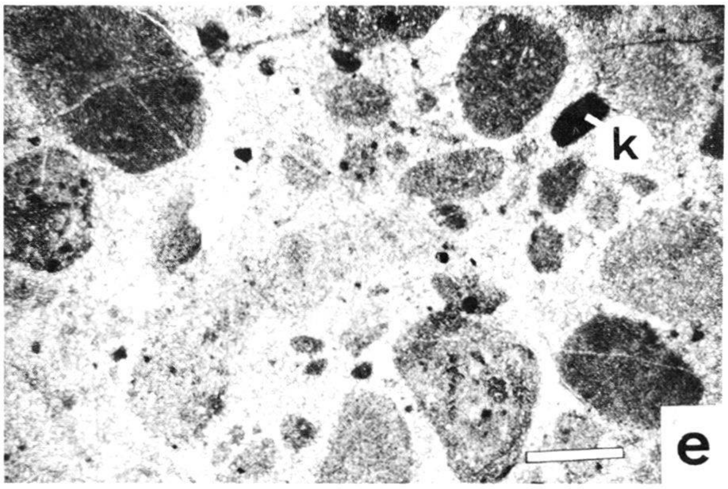
b: Same as in a, showing ultracataclasite matrix with idiomorphic dolomite crystals (d) and two clasts of oolitic Hauptdolomit, the left one with microfractures (mf).



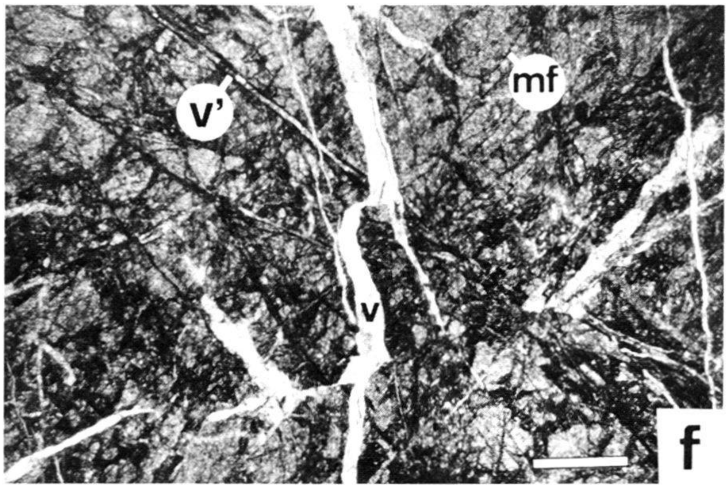
c: Liassic cataclasite. Sparitic Hauptdolomit clast in an advanced stage of fracturation. Dark matrix is produced along irregular fractures cutting the clast.



d: Liassic cataclasite, partly recrystallized. Stylolitic seams (dark) develop in the matrix and around clasts. Thin veins (v) cut straight through clasts and matrix.



e: Liassic cataclasite, strongly recrystallized. Most clasts are Hauptdolomit, (k) is a Kössen limestone that did not recrystallize due to high clay content. Former ultracataclastic matrix completely recrystallized.



f: Alpine Hauptdolomit cataclasite with microfractures (mf), ultracataclasite (dark), several generations of irregular veins (v) and veins established within earlier ultracataclasite-bearing fractures (v′).

— The occurrence of "secondary clasts" shows that fault movement was dicontinuous, allowing induration of the cataclasite between individual faulting episodes.
— In the time span between their formation and the Alpine deformation, the fault rocks were affected by diagenetic processes and recrystallization leading to the present well-lithified cataclasites. This is one reason why the faults where not inverted by Alpine deformation. Another reason is that they were unsuitably oriented for Alpine reactivation.

Fault rocks from Alpine normal faults within the Hauptdolomit are generally much less indurated than the Liassic ones. Poorly cemented fault breccias with open voids are common. In thin sections, Alpine cataclasites show several generations of shear fractures, cataclastic zones, veins, and stylolites. The fabric is very similar to the dolomite cataclasites from the Saltville thrust (USA) described by House & Gray (1982). The veins are mostly younger than the shear fractures (Fig. 8f), but the opposite case also occurs. Veins are often established within earlier ultracataclasite-bearing shear fractures, showing that the cataclasite was not yet or poorly indurated. Figure 9 shows a polyphase fault rock produced by Alpine brittle deformation of a Liassic cataclasite: The older fabric is a Liassic cataclasite containing "secondary clasts" of earlier cataclasite. This rock was partly recrystallized after the Liassic cataclasis. Alpine deformation is represented by formation of veins, a thin cataclastic shear fracture cutting these veins, and stylolites.

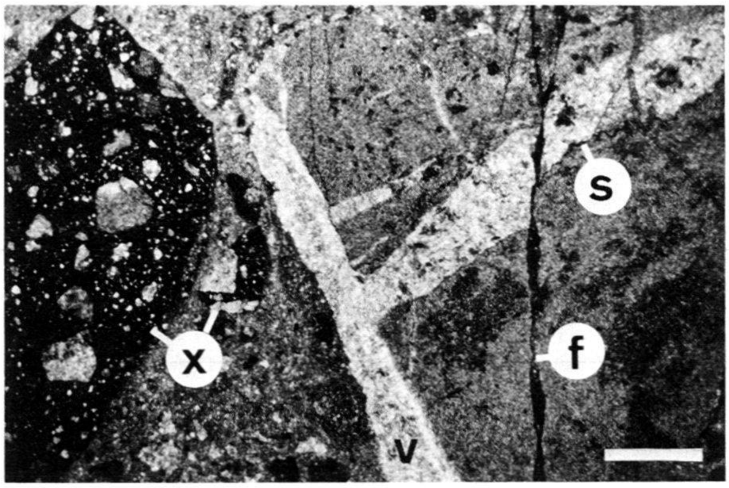


Fig. 9. Photomicrograph of partly recrystallized Liassic cataclasite with clasts of slightly older cataclasite (x), overprinted by Alpine brittle deformation with veins (v), cataclastic shear fracture (f), and stylolites (s). Scale bar is 1 mm long.

Conclusions

In the western part of the Ortler zone, Liassic synsedimentary normal faults are preserved. The synsedimentary fault activity is reflected by carbonate resediments within the Liassic Allgäu beds (synrift sediments). The faults were not reactivated during Alpine thrusting for two reasons:

1. The Liassic extension direction (E–W) was not identical with the direction of Alpine compression. The latter was first SE–NW (F1-folds in the Allgäu Beds) and later NE–SW (Quattervals thrust).
2. Between their formation and the Alpine deformation, dolomite cataclasites along Liassic fault planes were highly indurated by diagenesis and recrystallization.

Reconstruction of the Liassic fault geometry indicates extension of the Triassic prerift sediments by rotational planar faults (domino mechanism). The faults dipped to the east, i.e. in a direction away from the future Piemont Ocean which opened farther to the west during the Middle/Late Jurassic. This is consistent with Liassic fault geometries observed in other tectonic units of the Eastern Alps (EBERLI 1988) and in the western part of the Southern Alps (BERNOULLI 1964, SCHMID et al. 1987). The fault geometry indicates that extension of the prerift sediments was rather substantial; a first, very crude estimate gives an extension ratio of 1.3 to 1.65. More accurate estimates can only be made by restoring sections on a regional scale.

Alpine normal faults cutting the Hauptdolomit of the study area are not due to crustal-scale extension, but developed during Alpine thrusting as a response to the different lithological properties of the Hauptdolomit and the over- and underlying, less competent strata. The Alpine normal faults accommodated domino style extension of the Hauptdolomit in a SE–NW direction. This can be explained by NW-directed simple shear, or by "extrusion" of the Hauptdolomit between two basement blocks thrusted one over the other (SCHMID & HAAS, submitted), or by a combination of both effects.

In the study area, Hauptdolomit cataclasites from synsedimentary and from Alpine normal faults can be clearly distinguished by microstructural criteria. These criteria may become an important tool for the recognition of synsedimentary faults in areas where no synrift sediments are preserved.

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