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Synrift sedimentation, Jurassic and Alpine tectonics in the central Ortler nappe (Eastern Alps, Italy)

PAOLO CONTI[1], GIANRETO MANATSCHAL[2] & MICHAEL PFISTER[3]

Key words: Austroalpine, Jurassic extensional tectonics, rift-related sedimentation, inversion tectonics, Alpine deformation

ABSTRACT

New evidence for Early Jurassic rifting is presented for the Austroalpine Ortler nappe (Eastern Alps, Italy) in the area between Livigno and Valle di Fraele. Active fault scarps are documented by the presence of megabreccias, conglomerates and calcarenites in the Liassic Allgäu Formation and by an angular unconformity that connects eastward to the east-dipping Monte Torraccia normal fault. This normal fault can be followed for a distance of more than 5 km. New findings of ammonites document that carbonate redeposition and tectonic activity along the fault initiated during the Late Hettangian.

Two main phases of Alpine deformation can be recognized. The first, late Cretaceous phase is characterized by westnorthwest-directed thrusting, nappe emplacement and mylonite formation along the Quattervals thrust and the Zebrù thrust. At the same time sediments of the Ortler nappe were affected by open to isoclinal folding and west-thrusting, accompanied by reactivation of the M. Torraccia Jurassic normal fault that led to the inversion of the Jurassic sedimentary basin. During a later, probably Tertiary deformation phase large scale folds with northwest-southeast oriented fold axes developed. This phase did not essentially alter the geometry produced by the first one, but is responsible for the general north-dip of bedding and nappe contacts in the area.

ZUSAMMENFASSUNG

Hinweise auf liasische Extensionstektonik im Gebiet zwischen Livigno und Valle di Fraele (Zentrale Ortler-Decke) geben einerseits die Megabreccien, Konglomerate und Kalkarenite innerhalb der Allgäu-Formation, andererseits eine stratigraphische Diskordanz am Monte Torraccia, die ostwärts in einen ostfallenden, alpin reaktivierten, steilen Normalbruch übergeht. Dieser Bruch kann über eine Distanz von 5 km verfolgt werden. Neue Funde von Ammoniten ermöglichen eine präzise Einstufung des Beginns der tektonischen Aktivität ins späte Hettangian.

Strukturgeologische Untersuchungen zeigen einerseits eine Überprägung der jurassischen Strukturen durch die alpine Tektonik, andererseits können zwei alpine Hauptdeformationsphasen erkannt werden. Eine erste Deformationsphase führte zu einem westgerichteten Deckentransport. Zusammen mit diesem Deckentransport entstanden entlang der Zebrù-Überschiebung am Kontakt zum darunterliegenden Campo-Kristallin und entlang der Quattervals-Überschiebung Mylonite. Gleichzeitig mit der Deckenüberschiebung kam es deckenintern zur Ausbildung von grossräumigen Isoklinalfalten sowie von Überschiebungen, die zu einer Inversion der sedimentären jurassischen Becken führt.

Eine spätere Deformation (D3) zeigt grossräumig angelegte Ost-West-streichende Grossfalten, die für die heutige Steilstellung der Ortler-Decke im Gebiet zwischen Livigno und Valle di Fraele verantwortlich sind.

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[1] Geologisch-Paläontologisches Institut, Universität Basel, Bernoullistrasse 32, CH–4056 Basel

[2] Geologisches Institut, ETH-Zentrum, CH–8092 Zürich

[3] Institute of Marine Affairs, Hilltop Lane, Chaguaramas, Trinidad & Tobago

RIASSUNTO

In questo lavoro è riportato un esempio di sedimentazione legata alle fasi di rifting giurassico nella falda Austroalpina dell'Ortles, tra Livigno e la Valle di Fraele. Megabrecce, conglomerati e calcareniti presenti nell'area a N di Monte Torraccia si sono deposti in prossimità di una faglia diretta di età giurassica cartografabile per una lunghezza di oltre 5 km. Sono state inoltre riconosciute due principali fasi deformative alpine. Alla prima fase deformativa sono riferibili: la messa in posto delle falde, caratterizzate da un movimento generale di trasporto tettonico verso WNW, la formazione di miloniti lungo l'accavallamento dello Zebrù e l'accavallamento di Quattervals; lo sviluppo di pieghe isoclinali e di lineazioni d'estensione, la riattivazione della faglia diretta giurassica del Monte Torraccia come superficie di accavallamento ed infine l'inversione del bacino sedimentario giurassico. Una fase di piegamento tardiva non altera sostanzialmente il quadro strutturale creato dalla prima fase deformativa; essa produce solamente pieghe a grande scala responsabili dell'attuale immersione generale verso N di tutta la Falda dell'Ortles.

1. Introduction

During the last years the geometry, kinematics and mechanics of crustal extension and the early evolution of the passive continental margins of the Jurassic Tethys ocean have become a major topic of geological research in the Alps. Remnants of the Southern continental margin are partially well exposed in the Austroalpine nappes of the Eastern Alps, where in spite of Cretaceous and Tertiary deformation the geometry of synsedimentary fault systems and the associated facies distribution may be still recognized (Furrer 1985; Eberli 1988; Froitzheim 1988; Bernoulli et al. 1990; Froitzheim & Eberli 1990). Unravelling the geometry of the rift-related normal faults is of first importance for understanding Alpine deformation as their presence strongly controls the development of later Alpine thrusts. If such faults are suitably oriented, they can be reactivated, leading to the inversion of the sedimentary basin (Hayward & Graham 1989; Letouzey 1990; McClay & Buchanan 1992). In this paper we report an example of Jurassic tectonics, rift-related sedimentation and interference with Alpine thrusting from the Ortler nappe in the Austroalpine system of the Engadine Dolomites.

2. Regional setting

The study area (Fig. 1) is located in the central part of the Ortler nappe, between Livigno and Valle di Fraele. The Ortler nappe is the southernmost unit of the Engadine Dolomites nappe stack. It is overlain by the Quattervals nappe, and tectonically overlies the basement rocks of the Campo nappe, both belonging to the Upper Austroalpine domain. In the Austroalpine nappes of the Engadine Dolomites the following Alpine deformation phases have been recognized:

D1 – (Cretaceous). This is the main orogenic phase during which nappe emplacement, regional west-directed thrusting and most of the internal nappe deformation occurred. This phase, the *Trupchun phase* of Froitzheim et al. (in press) is recorded all over the Eastern Alps (Ratschbacher 1986; Ring et al. 1988; Schmid & Haas 1989). It is probably coeval with the deposition of the Upper Cretaceous Gosau beds of the Northern Calcareous Alps (Ratschbacher et al. 1989).

D2 – (Late Cretaceous). Northwest of the Engadine line, east-west extensional normal faults and recumbent folds developed contemporaneously in the Austroalpine area (Froitzheim 1992). It is reported as *Ela-Ducan* phase by Froitzheim et al. (in press).

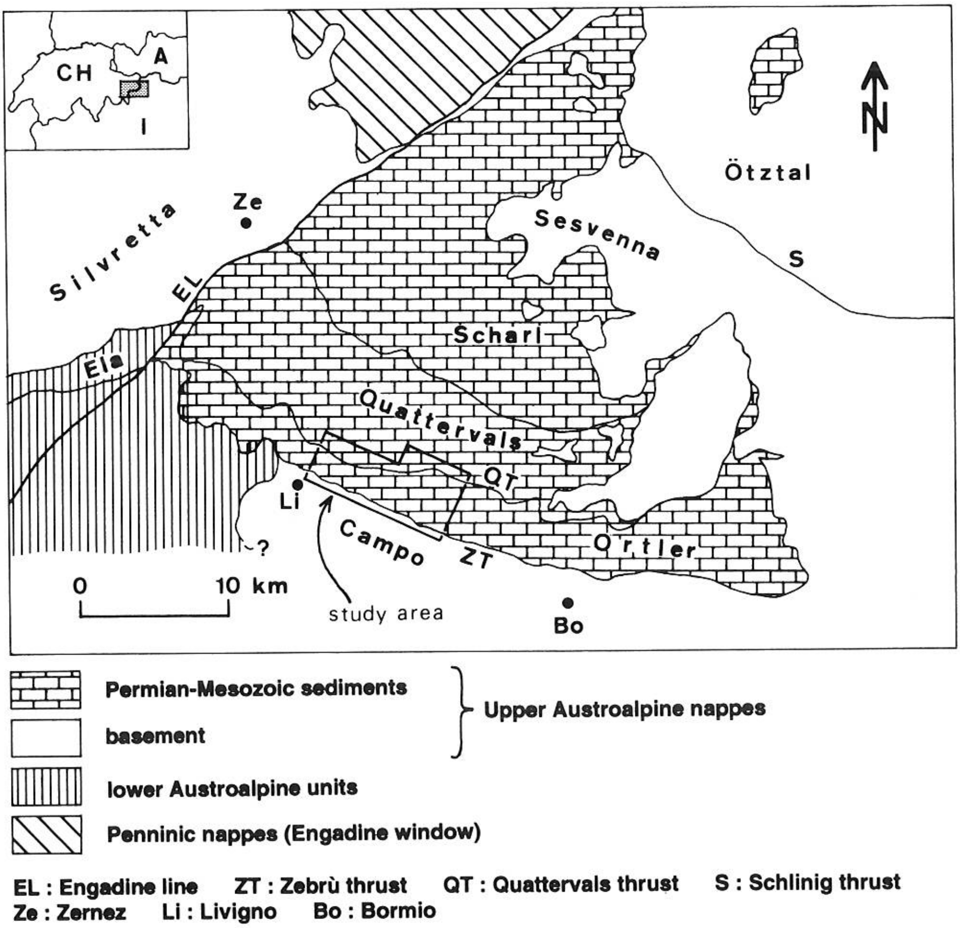

Fig. 1. Tectonic sketch map of the Engadine Dolomites area, simplified after Spicher (1980).

Southeast of the Engadine line, D2 extensional faulting is only documented at the western end of the Ortler nappe (Val Trupchun), where sediments of the Ortler nappe directly overly Lower Austroalpine flysch along an east-dipping normal fault, the Trupchun normal fault (Schmid & Froitzheim 1993), and the Campo nappe is omitted.

D3 – (Eocene). During north-thrusting of the Austroalpine edifice over Middle and North Penninic units, the entire nappe pile was refolded into upright open folds with westnorthwest-eastsoutheast trending axes, the *Blaisun phase* of Froitzheim et al. (in press).

D4 – (Oligocene). Ongoing shortening during the Tertiary produced complicated block rotation and oblique slip along the Engadine line (Schmid & Froitzheim 1993). In the Engadine Dolomites area, these movements resulted in normal faulting and east-west extension. The whole nappe stack was downfaulted and juxtaposed with the Ela and Silvretta nappes.

In spite of the fact that direct field evidence for D2 and D4 is lacking in the study area, the above nomenclature is adopted here in order to facilitate comparisons with other areas of the Austroalpine nappe system of eastern Switzerland.

3. Stratigraphy

a. Pre-rift sediments

There are only three areas in the entire Ortler nappe, where basement and Permian-Triassic sediments can be found stratigraphically underlying Jurassic and younger sediments (Pozzi 1957; Martina 1958; Pozzi 1959; Furrer 1981; Eberli, 1985). These areas are from west to east: Piz Chaschauna, Il Motto and Alpe Trela-Monte Pettini. All three places lie close to preserved near-surface, Mesozoic high-angle normal faults. In the following, the stratigraphy between Alpe Trela and Monte Pettini will be briefly discussed, with emphasis on new observations only (Fig. 2). Further details of the stratigraphy of the Austroalpine Permian-Triassic and Jurassic sediments are reported by Dössegger (1974), Furrer (1981), Dössegger et al. (1982), Eberli (1985), Frank (1986) and Naef (1987).

A slice of Variscan coarse-grained leucocratic gneiss (Gneiss Chiaro; Stella 1894) locally preserved above the D1 Zebrù thrust and consisting of quartz, plagioclase, K-feldspar and muscovite, forms a flat band of 3.5 km length between Passo Trela and Monte Trela. The maximum thickness is 150 m. The tectonic contact between the Gneiss Chiaro and the basement of the underlying Campo nappe is the Zebrù thrust. The Gneiss Chiaro is covered by 25 m of red volcanic rocks of rhyodacitic composition which we informally call the Trela Volcanics (Manatschal 1991). Because of the strong Alpine deformation it is not possible to decide whether these were originally rhyodacitic lavas, layered ash tuffs or ignimbrites. A basaltic dyke east of Alpe Trela (coordinates of Swiss topographic map 815.750/155.900, 2380 m a.s.l.) crosscuts the Gneiss Chiaro and can be followed into the overlying Trela Volcanics. XRF data from this dyke indicate a basaltic composition, quite different from the rhyodacitic Trela Volcanics or from the Permian rhyolitic dykes of the Lower Austroalpine Bernina nappe (Rageth 1984). The composition of these dykes correlates better with the alcalibasalts of Döss Radond and Val Mora (S-charl nappe), that are supposed to be of Ladinian age (Frank 1986). If these dykes are indeed of Triassic age, the contact between the volcanics and the Gneiss Chiaro must be stratigraphic.

The Trela Volcanics are overlain by the Chazforà Formation (Dössegger 1974) consisting of layered red conglomerates, sand- and siltstones with clasts of volcanic and crystalline basement rocks. The Chazforà Formation shows a fining upward trend with a maximum thickness of about 200 m. The overlying Fuorn Formation (Dössegger 1974) is characterized by a change in colour from red to yellow and by the appearance of dolomites, interbedded with laminated and graded sand- and siltstones. In the study area, the Fuorn formation is only 8 m thick, but this reduced thickness may be due to Alpine thrusting. In analogy with similar series from other Austroalpine units, the Trela Volcanics and the lower part of the Chazforà Formation are assumed to be of Permian age, whereas the upper part of the Chazforà and the Fuorn Formations could be Early Triassic.

The overlying dolomites of the Buffalora Group (Dössegger & Müller 1976) may be divided into three different formations: the lower, well-bedded, dark grey, about 30 m

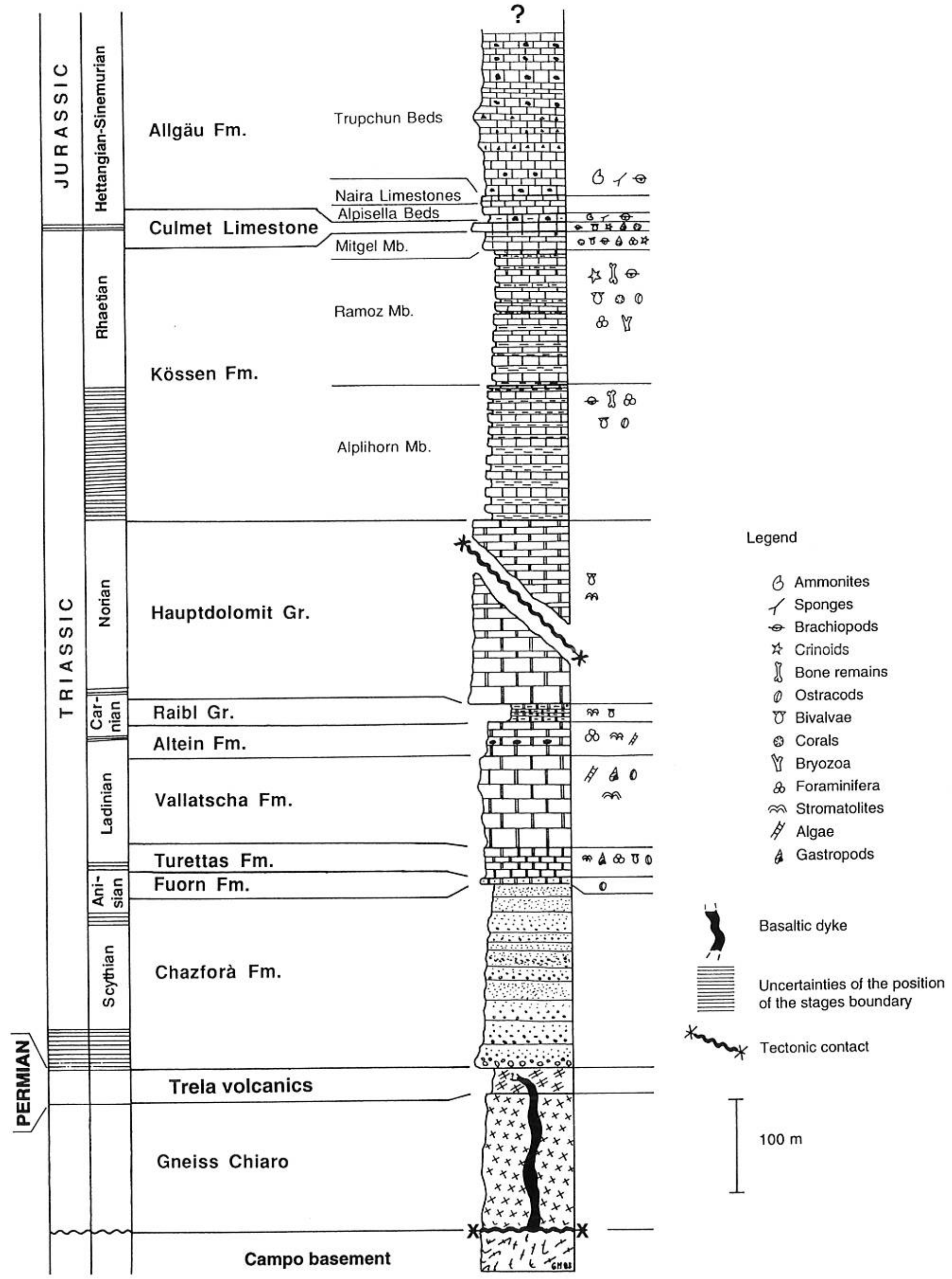

Fig. 2. Cumulative stratigraphic section in the Alpe Trela-M. Pettini area.

thick Turettas Formation; the middle, light grey, 100 m thick Vallatscha Formation, which frequently yields calcareous algae *(Diplopora annulata* SCHAFHÄUTL), and the upper, thin-bedded, chert- and tuff-bearing Altein Formation (Frank 1986) with a maximal thickness of about 30 m. All three formations show evidence of deposition in an inter- to supratidal environment, however, the strong recrystallisation of the dolomites prevents a more detailed interpretation. The dominant algal taxon, *Diplopora annulata,* in the Vallatscha Formation suggests a Ladinian age for this formation (cf. Ott 1972).

The overlying Raibl Group and Hauptdolomit Group are strongly affected by Mesozoic faulting and Alpine thrusting, hence they do not preserve the original thickness. The Raibl Group has a maximum thickness of 15 m and consists of thin-bedded dolomites and shales. Cornieules, gypsum or red sandstones (Cluozza Sandstone) which are typical lithologies of the Raibl Group elsewhere are missing in the Alpe Trela area.

The Hauptdolomit Group (Gelati in Bonsignore et al. 1969) is built up of light-coloured dolomites, which up-section change into dark grey, well-bedded dolomites. Thickness increases from zero to about 1000 m along a distance of 3.5 km from Passo Trela to Cima Doscopa. This abrupt change in thickness is essentially a consequence of Alpine tectonics. However, primary thickness variations are also present: as schematically represented in Figure 15a, the Hauptdolomit at Cima Doscopa area is primarily thicker than that of Monte Torraccia.

The overlying Kössen Formation (Furrer 1981) shows a large variety of lithologies such as dark shales, marls, limestones and dolomites, often rich in fossils. An increase in carbonate and a decrease in terrigeneous clastics can be observed from the base to the top of the formation. The Kössen Formation can be subdivided into three members (Furrer 1981). The basal Alplihorn Member (150 m thick), and the overlying Ramoz Member (140 m thick) are dominated by shales, marls, laminated siltstones, coral limestones, tempestites and thin-bedded yellow dolomites. The uppermost Mitgel Member (20 m thick) consists of well-bedded laminated siltstones, oolites and limestones. Detailed sections of the Kössen Formation north of Monte Pettini (Manatschal 1991) were subdivided into several facies types, as proposed by Furrer (1981). 58 mostly incomplete cycles can be recognized within the Alplihorn- and the Ramoz-Member. The most probable facies successions have been subsequently determinated according to the statistic method of Hay (1972). These consist of shale-tempestite-laminated dolomite in the case of the Alplihorn Member and of shale changing upsection to marl-laminated and dolomite-tempestite-arenitic limestone in the case of the Ramoz Member. Gradational facies change has been observed, whereas the beginning of a new facies succession is always very abrupt. Similar cycles in Upper Triassic siliciclastic rock and carbonates of the Southern Alps were interpreted by Masetti et al. (1988) as a record of short periodic relative sea-level and climatic changes influencing sedimentation.

The Kössen Formation is overlain by the Culmet Limestone (Furrer 1981), a 10 m thick, massive, light grey limestone with chert nodules and dolomitized patches. This limestone is a good marker-bed between the Kössen and the Allgäu Formation and allows the determination of the original bed-length within the strongly folded Ortler nappe (see below).

The youngest sediments exposed are marls and limestones, interbedded with different types of redeposited sediments, such as breccias, conglomerates and graded calcarenites.

These sediments are part of the Liassic Allgäu Formation, which will be discussed in the next paragraphs.

b. *Liassic synsedimentary normal faults*

Evidence for Early to Middle Jurassic crustal extension in the Austroalpine realm and in the Southern Alps was provided by sedimentological and structural studies by Bernoulli (1964), Castellarin (1972), Eberli (1985; 1987; 1988), Handy (1987), Schmid et al. (1987), Froitzheim (1988), Froitzheim & Eberli (1990), Bertotti (1991) and others. Furrer (1981), Dössegger et al. (1982) and Eberli (1985) analysed the redeposited sediments, the basin geometry and the depositional pattern of the Liassic synrift sediments in the central Austroalpine. Eberli (1987) showed that the sediments of the Allgäu Formation are characterized by thinning and fining upward megacycles, accumulating after discrete rifting events. He also proposed that the apron-like distribution of resediments reflected line sources along the fault scarps rather than submarine fans. Likewise the asymmetry of the basins determined the overall depositional geometry of the sediments.

Liassic synsedimentary normal faults are preserved in the western part of the Ortler nappe as shown by Froitzheim (1988) by detailed mapping and sedimentological and structural data. Good examples of these Jurassic normal faults, originally dipping to the east, have been reported at Piz Chaschauna and Il Motto, west of Livigno.

Whereas the features of Liassic synsedimentary normal faults and of the related sediments are well known in the area west of Livigno, the eastern area remained less investigated. As the Liassic basinal sediments provide an excellent record of the rifting history, we shall focus in the following section on these fault-related sediments in the area between Livigno and Valle di Fraele.

c. *Liassic sediments*

The Allgäu Formation forms sedimentary prisms accumulated during Jurassic rifting in tilted fault-block-basins. In the area between Livigno and Valle di Fraele, the Allgäu Formation can be divided into three members (Fig. 3). The basal member, known as Alpisella Beds (Furrer 1981) consists of bioturbated, fossiliferous, chert-bearing, regularly alternating marls and limestones, interbedded with different types of redeposited carbonate sediments including breccias, conglomerates and graded calcarenites. There is an increase in the proportion of background sediments from west (La Parè) to east (Monte Pettini). Whereas resediments gradually pinch out and thickness decreases from 120 m to 15 m. The overlying Naira Limestone (Furrer 1981) consists of well-bedded, dark limestones with fewer marl intercalations and yellow chert nodules; resediments are lacking. The thickness of this member decreases from about 50 m in the west to 20 m in the east.

The Trupchun Beds (Eberli 1985) are the highest member of the Allgäu Formation in the study area. They are similar to the Alpisella Beds and consist of breccias, conglomerates and calcarenites and of marl/limestone alternations, representing the background sedimentation. The ratio between redeposited and background sediments decreases eastwards and up-section, so that in the area east of Cima di Pozzin resediments become rare in the Trupchun Beds.

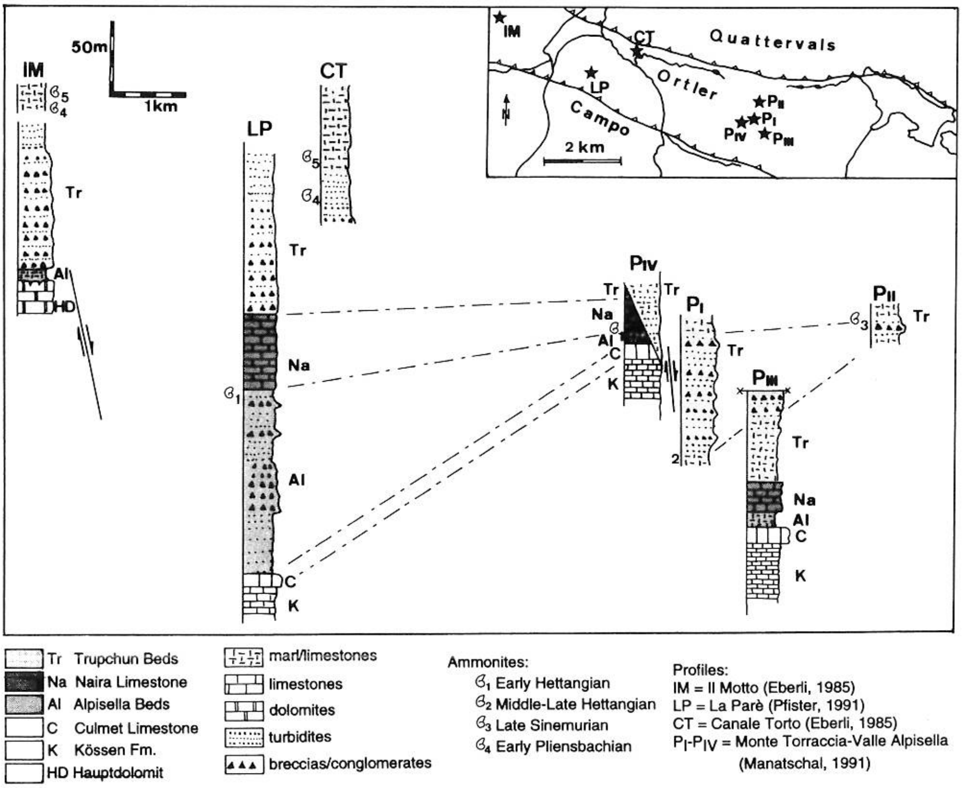

Fig. 3. Stratigraphic profiles of the Liassic Allgäu Formation in the central Ortler nappe.

North of M. Torraccia, a 100 m thick band of redeposited carbonates appears abruptly in the Trupchun Beds (Fig. 3, 4 and 7). These resediments are intercalated between bioturbated, resediment-free marl/limestone alternations. The resediments are dominated by thin-bedded, fine-grained calciturbidites that often show only the basal Bouma interval, whereas ripple and convolute lamination are missing (Fig. 4a). The turbidites are interbedded with bioturbated hemipelagic marls. Overall, the sequence shows a thickening- and coarsening upward trend. The conglomerates become more frequent upward

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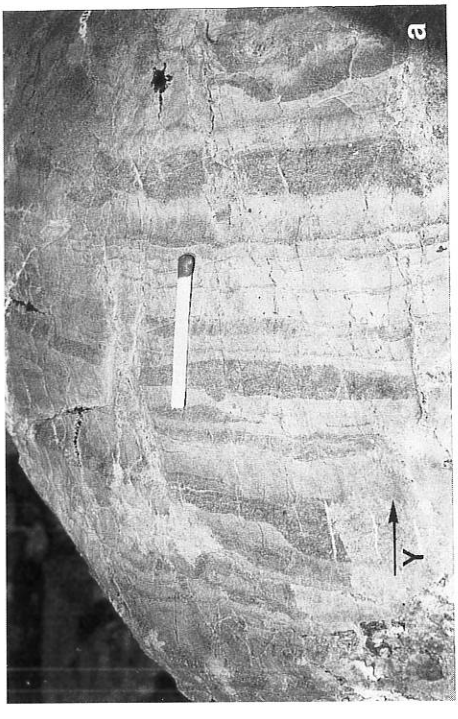
Fig. 4. a) Thin-bedded, graded and laminated (Ta, Tab. rare Tabc) calcarenites. Erosion structures occur at the base of one of the turbidites. Trupchun Beds, north of M. Torraccia, along profile P_I of Fig. 7, younging direction (Y) to the right; b) Grain supported conglomerate (K) with clasts derived from the Kössen and Allgäu Formations. The conglomerate is overlain by a turbidite (T) (right side). (A = *Schlotheimia montana*); Trupchun Beds outcrop north of M. Torraccia; c) Decametric block derived from the Kössen Formation in a conglomerate of the Allgäu Formation (Trupchun Beds, north of M. Torraccia); d) Turbidite clast (T) in a megabreccia of the Allgäu Formation (Trupchun Beds, north of M. Torraccia, near profile P_{II} of Fig. 3 and Fig. 7).


a
Y


b
T
T
A
Y


c


d
T

and pass into a megabreccia. Still higher up, debris flow deposits overlain by turbidites are present (Fig. 4b). These conglomerates yield angular to moderately rounded components of the Kössen and the Allgäu Formation up to 10 cm across. Most conglomerates are grain-supported and form continuous flat layers. In the upper part of the resediments, up to 100 m long blocks of silicified Kössen limestone occur in a debris sheet (Fig. 4c). Clasts of calciturbidites in these deposits show that reworking of basinal sediments also occurred (Fig. 4d). Up-section the megabreccias are in turn overlain by bioturbated marls and limestone. The observed coarsening upward cycle contrasts with the general thinning- and fining-upward megacycle described by Eberli (1985) for other resediments deposited in the early Jurassic rift-basins.

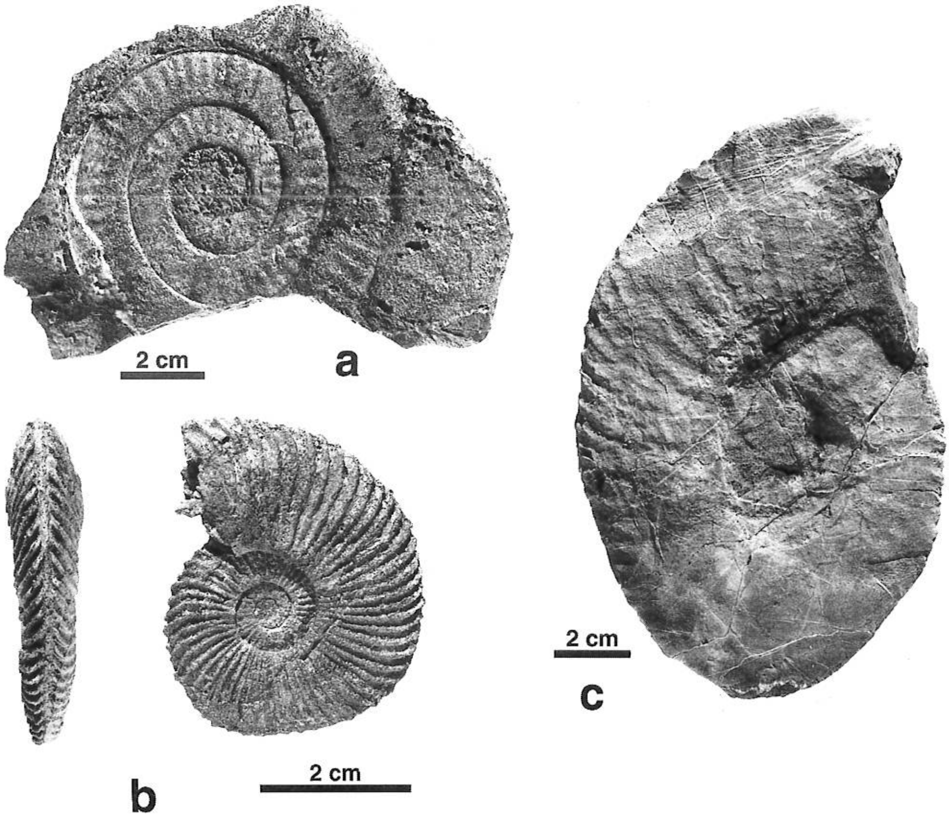


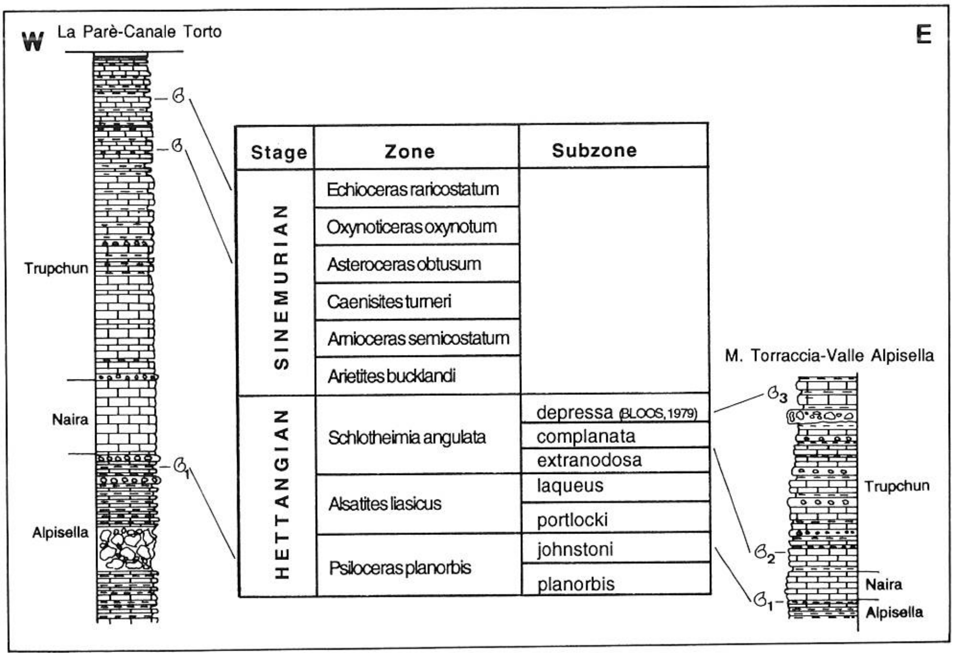
Fig. 5. Ammonites from the M. Torraccia-Valle Alpisella area; see Fig. 3 and Fig. 7 for locations. a) *Psiloceras naumanni* (NEUMAYR), Alpisella Member, north of M. Torraccia, Swiss coord. 812.700/158.150, 2640 m a.s.l.; b) *Schlotheimia montana* (WAEHNER), Trupchun Beds, north of M. Torraccia along profile P_{I}, Swiss coord. 812.900/158.250, 2550 m a.s.l.); c) *Angulaticeras* cf. *marmoreum* (OPPEL), Trupchun Beds, Valle Alpisella along profile P_{II}, Swiss coord. 812.750/158.875, 2335 m a.s.l.

d. *Age of the Allgäu Formation*

New findings of ammonites in the hemipelagic deposits of the Allgäu Formation east of Livigno (Fig. 5). together with earlier findings by Pozzi (1960), Furrer (1981), Eberli (1985), Nägeli (1985) and Dommergues & Meister (1990) allow for a detailed definition of timing of the tectonic activity in the different basins as well as for the dating of the different members of the Allgäu Formation. The ammonites are illustrated in Figure 5. They were determined by R. Schlatter and are deposited at the Paleontological Institute of the University of Zürich. An attempt at correlating the bio- and lithostratigraphy of the Allgäu Formation in the area between Livigno and Valle di Fraele is shown in Figure 6, based on these ammonite findings.

e. *The discordance north of Monte Torraccia, a relict of Jurassic extensional tectonics*

The area of M. Torraccia shows very strong Alpine deformation, with isoclinal D1 folds and younger normal faults (Fig. 7). D1 structures and bedding were subsequently brought into a steep position by large scale D3-folding. In the normal limb of the isoclinal D1 fold just north of M. Torraccia, the Allgäu Formation, the Culmet Limestone and



Stage	Zone	Subzone
SINEMURIAN	Echioceras raricostatum	
	Oxynoticeras oxynotum	
	Asteroceras obtusum	
	Caenisites turneri	
	Arnioceras semicostatum	
	Arietites bucklandi	
HETTANGIAN	Schlotheimia angulata	depressa (BLOOS, 1979)
		complanata
		extranodosa
	Alsatites liasicus	laqueus
		portlocki
	Psiloceras planorbis	johnstoni
		planorbis

Ꮾ$_1$: *Psiloceras naumanni* (NEUMAYR) Ꮾ$_2$: *Schlotheimia montana* (WAEHNER)
Ꮾ$_3$: *Angulaticeras* cf. *marmoreum* (OPPEL)
Ꮾ : finding by other authors (Pozzi, 1960; Eberli, 1985; Dommergues & Meister, 1990)

Fig. 6. Chrono- and lithostratigraphy of the Allgäu Formation in the study area. Ammonite zonation after Donovan (1961) and Bloos (1979).

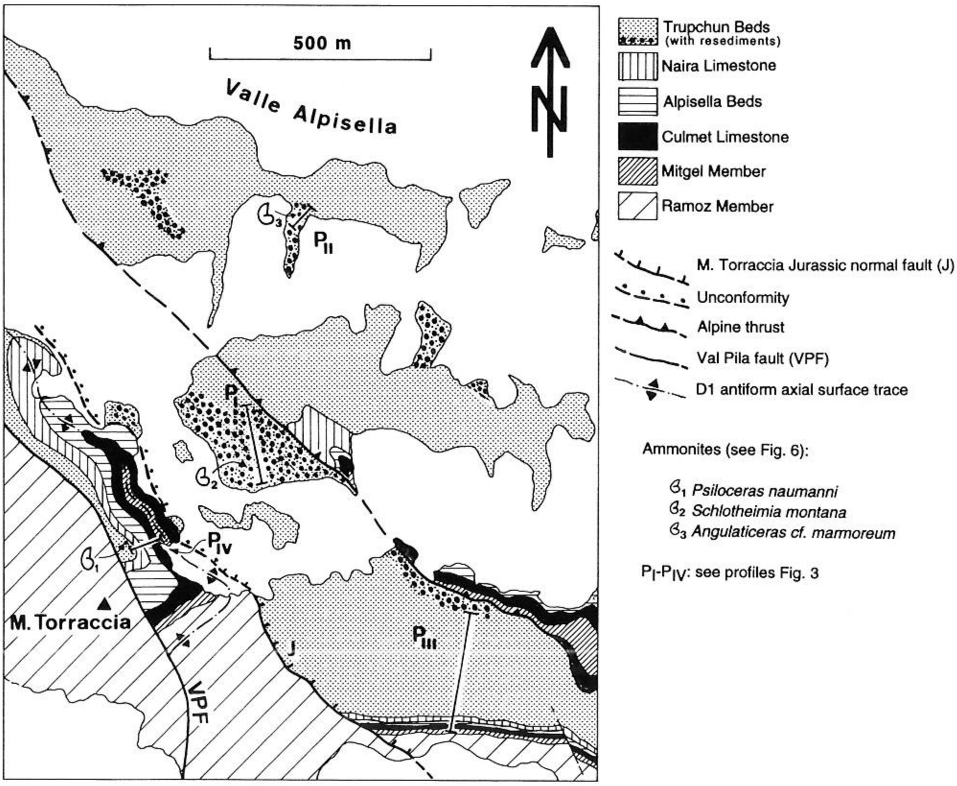


Fig. 7. Geological map of the M. Torraccia area.

most probably the Mitgel Member of the Kössen Formation disappear, going from west to east, over a distance of 0.5 km. There, the Trupchun Beds overly these formations with an angular unconformity. This angular unconformity passes eastward into a tectonic contact with a "younger-on-older" relationship, interpreted as a Liassic normal fault. This fault (J in Fig. 7 and Plate 1) can be followed east of M. Torraccia over a distance of more than 5 km, before it is cut by the Zebrù thrust (Plate 1). We propose that it is a relict of a Jurassic high-angle normal fault, which formed a fault scarp at the earth surface in Liassic time. The unconformity north of M. Torraccia is interpreted to result from tilting of the footwall block resulting in a submarine high, affected by erosion. Later the submarine high was buried by the Trupchun Beds. The high and the adjacent fault scarp were overprinted by D1-folding and thrusting which deformed the original Jurassic geometry. The superposition of Alpine D1 structures onto the fault geometry documents the proposed pre-Alpine age of the extensional fault.

The relation between bedding in the hangingwall, bedding in the footwall, and the fault surface changes from east to west along the M. Torraccia normal fault (Fig. 8 and Plate 1). East of Cima Doscopa, Hauptdolomit bedding in the hangingwall is parallel to the fault surface which in turn cuts the bedding of the Middle Triassic carbonates in the

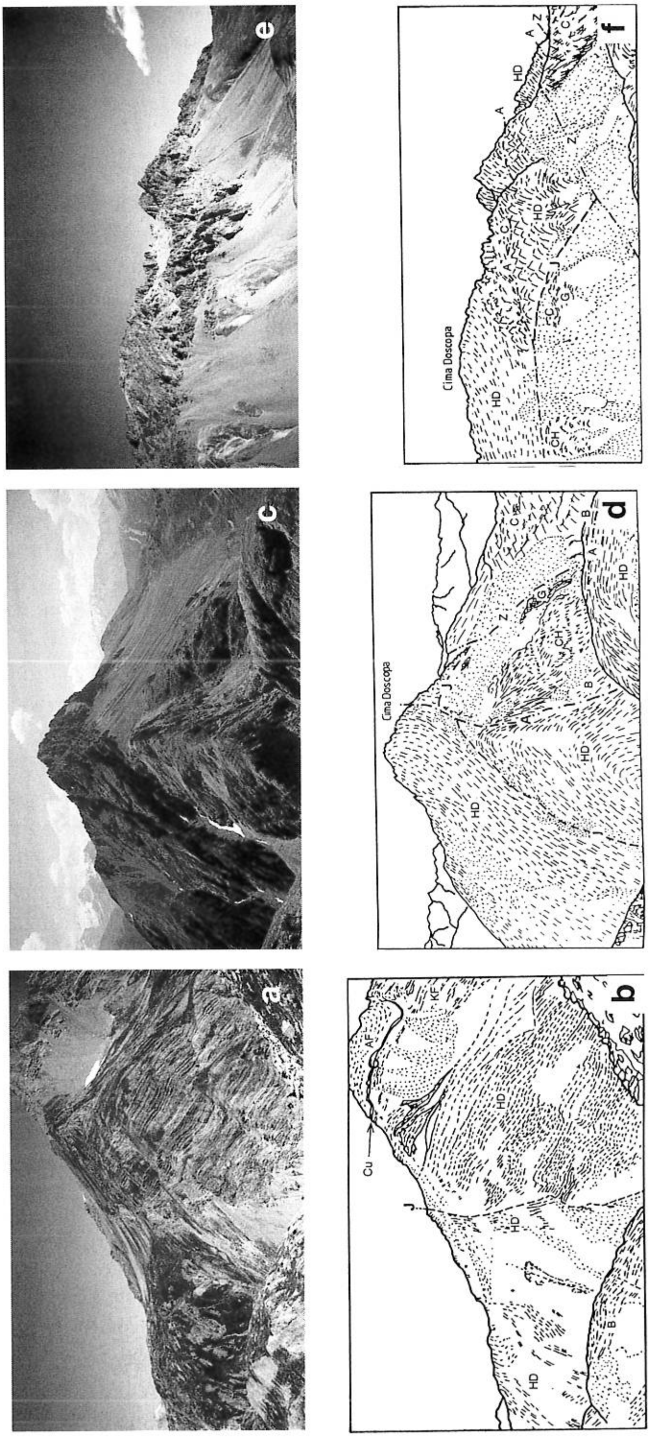


Fig. 8. Photographs (a, c, e) and drawning after photographs (b, d, f) of the Alpe Trela area.
a–b) The Monte Torraccia normal fault between Alpe Trela and M. Pettini, view is toward the west with north on the right. The top of M. Pettini is just outside the photo (upper right).
c–d) Cima Doscopa, view is toward the southeast with northeast on the left.
e–f) Cima Doscopa, view is toward the northeast with northwest on the left.
A = Alpine thrust plane, AF = Allgäu Fm., B = Buffalora Group (Middle Triassic carbonates), C = Campo basement, CH = Chazforà Fm., G = Gneiss Chiaro, HD = Hauptdolomit Group, J = Monte Torraccia normal fault, KF = Kössen Fm., Z = Zebrù thrust

footwall (Fig. 8b). By contrast, southeast of Monte Pettini (Fig. 8a) bedding in the hangingwall is at high angle with the normal fault and bedding in the footwall is parallel to the fault plane. Such a geometry is expected if the original fault plane, instead of having a simple listric geometry, followed ramps and flats (McClay & Buchanan 1992).

f. Evolution of Liassic normal faults and related sedimentation

Additional evidence for early tectonic activity in the area between Livigno and Valle di Fraele is provided by redeposited sediments in the Alpisella Beds (Fig. 9a). These resediments are dated by ammonites as early Hettangian (*Psiloceras naumanni, Curviceras waehneri, Discamphiceras* sp., Fig. 5). The strong decrease in the volume of resediments in the Alpisella Formation in comparison with the background sediments, and the decrease in the thickness of the sediment pile from 120 m (La Parè) to 15 m (Monte Pettini) eastwards, indicates the accumulation of a sediment prism directly related to fault activity at the Il Motto fault scarp (Eberli 1985; Furrer 1985). The culmet Limestone, a characteristic light-coloured limestone between the Kössen and the Allgäu Formation, allows the determination of the original distances (at least in the area west of M. Torraccia, where internal deformation can be neglected). The original distance between the fault scarp at Il Motto and Canale Torto, where the easternmost turbidites are found in the Alpisella Beds, was less than 5 km. This transport distance is rather small for turbidites and shows that the turbidity currents were stopped very quickly or deflected into a direction parallel to the basin. The thickness variations of the individual members of the Allgäu Formation, defining a wedgeshaped prism, are indicative for continuous rotation of the hangingwall fault block during extension. It is assumed that the shape of the sediment prism reflects the asymmetry of the basin, and that the resediments accumulated in the deepest areas near the fault. With this assumption the mean angle of rotation (α) between the hangingwall block and the horizontal after the sedimentation of the Alpisella Beds can be determined for the area La Parè-M. Torraccia (Fig. 10). From the thickness of the Alpisella Beds at la Parè and at M. Torraccia we obtain a mean tilt angle (α) of 1.2° during the first interval of tectonic activity in the early Hettangian. It is important to note that this angle does not represent the mean angle for the entire hangingwall rotation, but only for the area between la Parè and M. Torraccia. Approaching the Il Motto normal fault, bedding possibly was steeper in the hangingwall, due to a roll-over anticline geometry. However, since the base of the Alpisella-Beds is no longer preserved between Il Motto and La Parè above the Zebrù thrust, the Liassic depositional geometry cannot be restored for this area.

After the first rifting pulse documented by redeposited carbonates in the Alpisella Beds, the absence of resediments as well as the more constant thickness of the Naira Limestones (La Paré 50 m; Monte Pettini 20 m) indicate lesser or no tectonic activity during the sedimentation of the Naira Limestones.

Resediments in the Trupchun Beds from the western part of our area show a fining and thinning upward trend (Eberli 1985) and document that tectonic activity resumed along the Il Motto fault. In addition to the first extensional event, reflected by the sediment prism of the Alpisella Beds east of Il Motto, the Trupchun Beds document not only reactivation at the Il Motto fault but also a younger active fault in the area north of M. Torraccia-Valle Alpisella. Evidence for an eastern sediment prism linked to this fault is

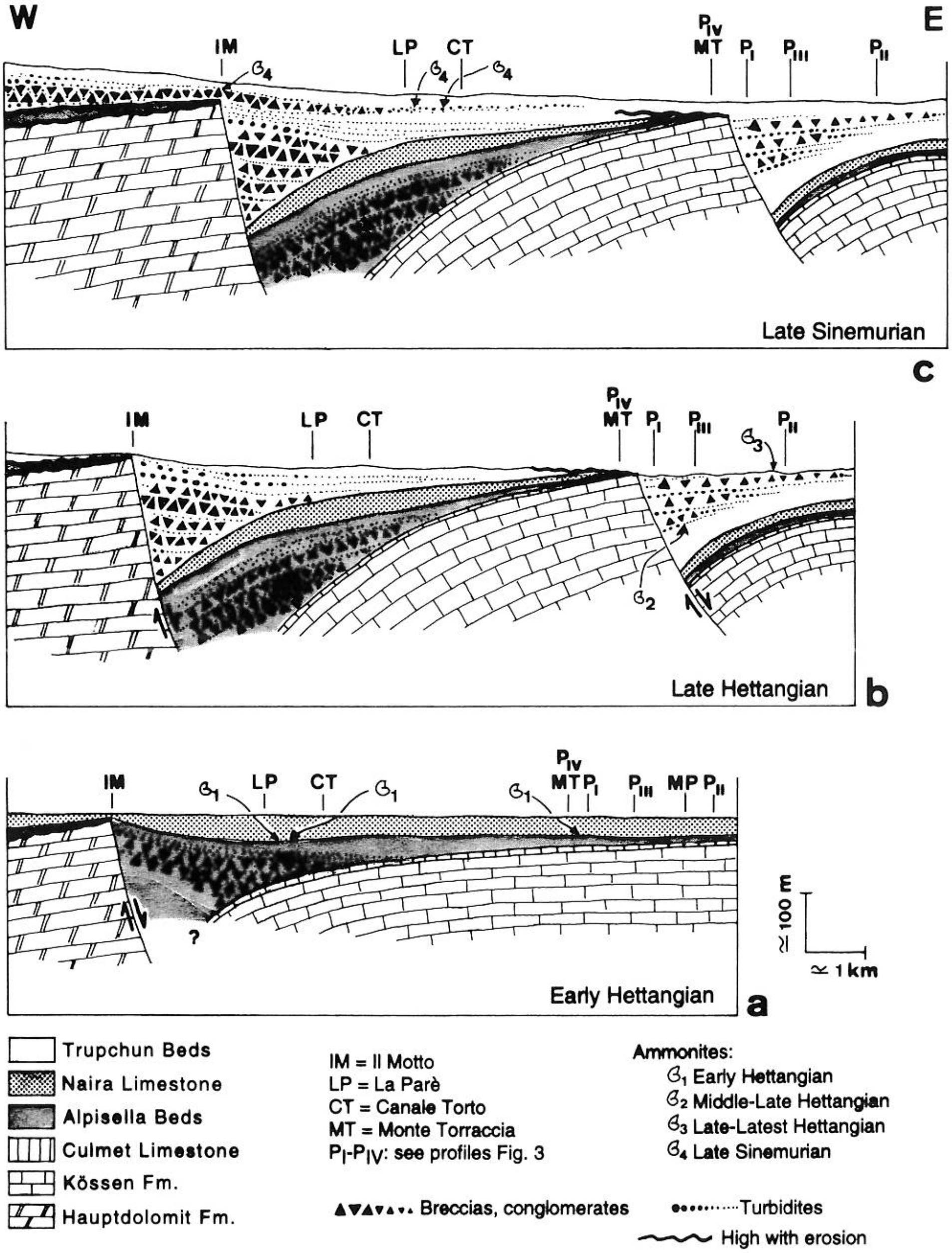
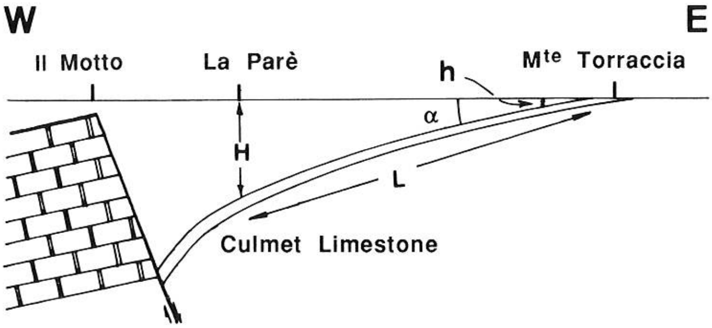


Fig. 9. Evolution of the Il Motto and M. Torraccia basins based on ammonite finding and sedimentological observations.



$$\alpha = \arcsin (H-h)/L$$

H = thickness of the Alpisella-Beds at La Parè (120m)
h = thickness of the Alpisella-Beds at Monte Torraccia (15m)
L = paleodistance (=length of the Culmet-Limestone) between La Parè and Monte Torraccia (5000m)

Fig. 10. Rough estimation of the hangingwall rotation during activity along the Il Motto normal fault (Early Hettangian-Late Sinemurian).

provided by the proximal resediments, megabreccias and conglomerates, associated with the Trupchun Beds north of M. Torraccia. These redeposited carbonates end abruptly towards the west, i.e. at the Liassic M. Torraccia fault, whereas eastwards they gradually decrease in bed thickness and grain size away from the sediment source. The most proximal redeposited carbonates can be found today just north of the Jurassic discordance adjacent to the Jurassic fault scarp. To the southeast, the underlying fault scarp can be reconstructed. This Jurassic high-angle normal fault can be followed from M. Torraccia to Cima Doscopa.

After corrections for the Alpine tectonic overprint, a complete, two-dimensional, near-surface high-angle normal-fault geometry with fault related sediments appears in the area between M. Torraccia and Cima Doscopa (Plate 1). Clasts derived from the Kössen Formation in the oldest resediment beds indicate that the Kössen Formation was exposed at the beginning of faulting. A significant morphological fault scarp thus developed early during faulting.

Based on biostratigraphical data (ammonites) the beginning of tectonic activity in the area of M. Torraccia – Valle di Fraele is dated as middle-late Hettangian (*Schlotheimia montana,* Fig. 5). The end of extensional movements in this area, documented by an ammonite found above the resediments, is dated as latest Hettangian (*Angulaticeras* cf. *marmoreum,* Fig. 9b). This means that the 100 m thick resediment section north of M. Torraccia was accumulated during a single ammonite subzone (abount 250,000 years) in the Late Hettangian. Because the overlying Trupchun Beds in Valle Alpisella do not bear any redeposited beds, the period of tectonic activity in the area of M. Torraccia must have been very short, compared with that of the Il Motto normal fault which was active from Early to Late Hettangian. The submarine high at Il Motto was buried in Early Sinemurian time (Furrer 1981; Eberli 1988), as indicated by a megabreccia association unconformably overlying the truncated Hauptdolomit. This indicates a westward stepping towards the future ocean of the fault related sediments and consequently of the tectonic activity (Eberli 1985).

We focus in this paper on Jurassic tectonics along the M. Torraccia normal fault, however we do not exclude the possibility that extension was also active in the Ortler nappe before the Liassic. Like in the Southern Alps, it may have been accomodated by thickness variations only, without the evolution of morphological fault-scarps and the deposition of related breccias (cf. Bernoulli et al. 1990). However, the strong Alpine tectonic overprint and the scarcity of complete stratigraphic sections do not allow for the recognition of abrupt changes in thickness.

4. Alpine deformation

a. Alpine deformation in the Ortler nappe

Parallel with the stratigraphical investigations detailed geological mapping (1:10,000) was carried out in order to investigate the Alpine deformation and to better reconstruct the original geometry of the synsedimentary normal faults. The study area is very suitable for structural field work, as the presence of shales, marls and limestones allows for a good development of axial plane cleavage in the strongly folded Kössen and Allgäu Formations. Facing directions of folds and relations between thrusting, folding and reactivation of Jurassic normal faults can thus be recognized.

After Jurassic extension the following deformation phases can be recognized in the Ortler nappe:

D1 phase

During this phase the Ortler nappe was thrust over the Campo nappe along the Zebrù thrust and in turn was overridden by the Quattervals nappe along the Quattervals thrust, also known in the geological literature as "Linea dell'Alpisella" (Bonsignore et al. 1969) or "Trupchun-Braulio Linie" (Schmid 1973). Thrusting of the Hauptdolomit of the Quattervals nappe onto the Allgäu Formation of the Ortler nappe produced plastic deformation and syntectonic recrystallisation in the underlying Liassic limestones, and calcite mylonites occur all along the Quattervals thrust (Fig. 11). Along the Zebrù thrust we can observe mylonitic deformation both in the underlying Campo basement (quartz mylonites) and in the Mesozoic sediments (calcite mylonites). Field evidence and microscopic shear sense indicators in mylonites indicate a top-to-the-westnorthwest transport direction both for the Zebrù thrust and the Quattervals thrust (Fig. 12a and 12b). Due to bad outcrop conditions in the mapping area, observations along the Zebrù thrust were made in immediately adjacent areas.

Below the Quattervals thrust, the Allgäu Formation is strongly folded. Approaching the thrust plane, the geometry of these D1 folds changes: the folds becomes tighter, the axial plane cleavage is more developed and a gradual transition into the calcite mylonites is observed. Close to the thrust plane, the fold axial planes curve asymptotically into parallel with the mylonitic foliation. Such a geometry is expected in areas of progressive deformation where thrusting, mylonite formation and folding occur at the same time. We

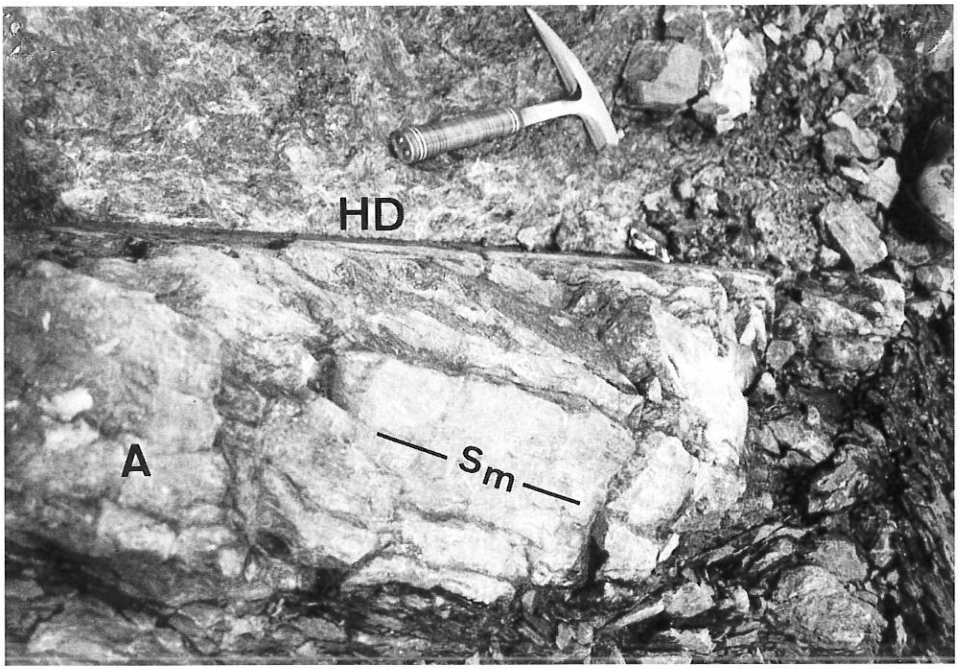


Fig. 11. Calcite mylonite from the Quattervals thrust.
HD=Hauptdolomit of the Quattervals nappe, A=Allgäu Fm. (Trupchun Beds) of the Ortler nappe, S_m=mylonitic foliation.

may therefore assume that D1 folding is contemporaneous with movements along the Quattervals thrust.

In the Kössen and Allgäu Formations of the Ortler nappe, D1 deformation produced open to isoclinal folds with a well-developed axial plane cleavage and stretching lineations parallel to the ones found along the Quattervals thrust and the Zebrù thrust (Fig. 12c).

Orientations of D1 fold axes are very variable in the area. In Figure 12d fold axes of large-scale folds are shown from the Valle Alpisella M. Pettini area. Since the D1 axial planes are constantly north-dipping, the variable orientation of fold axes cannot be attributed to a later folding event. Moreover fold axes lie on a great circle and the pole to this circle coincides with the maximum of the poles to the fold axial planes. From these observations, we can assume that dispersion of the fold axes occurred during D1. A possible mechanism to produce such non-cylindrical folding could be the reorientation of the early formed folds parallel to the transport direction during progressive simple shear deformation (Escher & Watterson 1974; Cobbold & Quinquis 1980). Sheath fold with north-dipping axial plane also occur in the Canale Torto-Cima di Pozzin area and in Valle di Fraele, these imply that non-cylindrical folding is not only a local effect of the interference between the Quattervals thrust and the reactivated M. Torraccia normal fault.

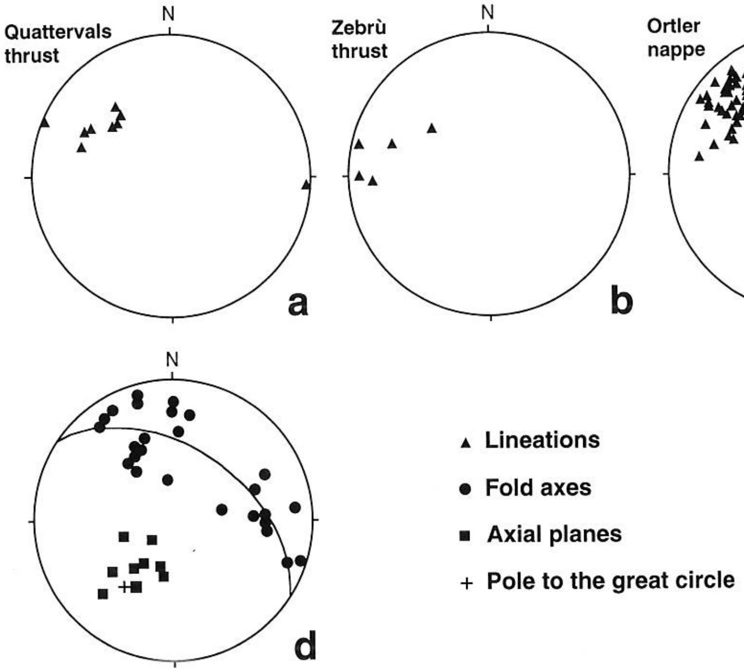


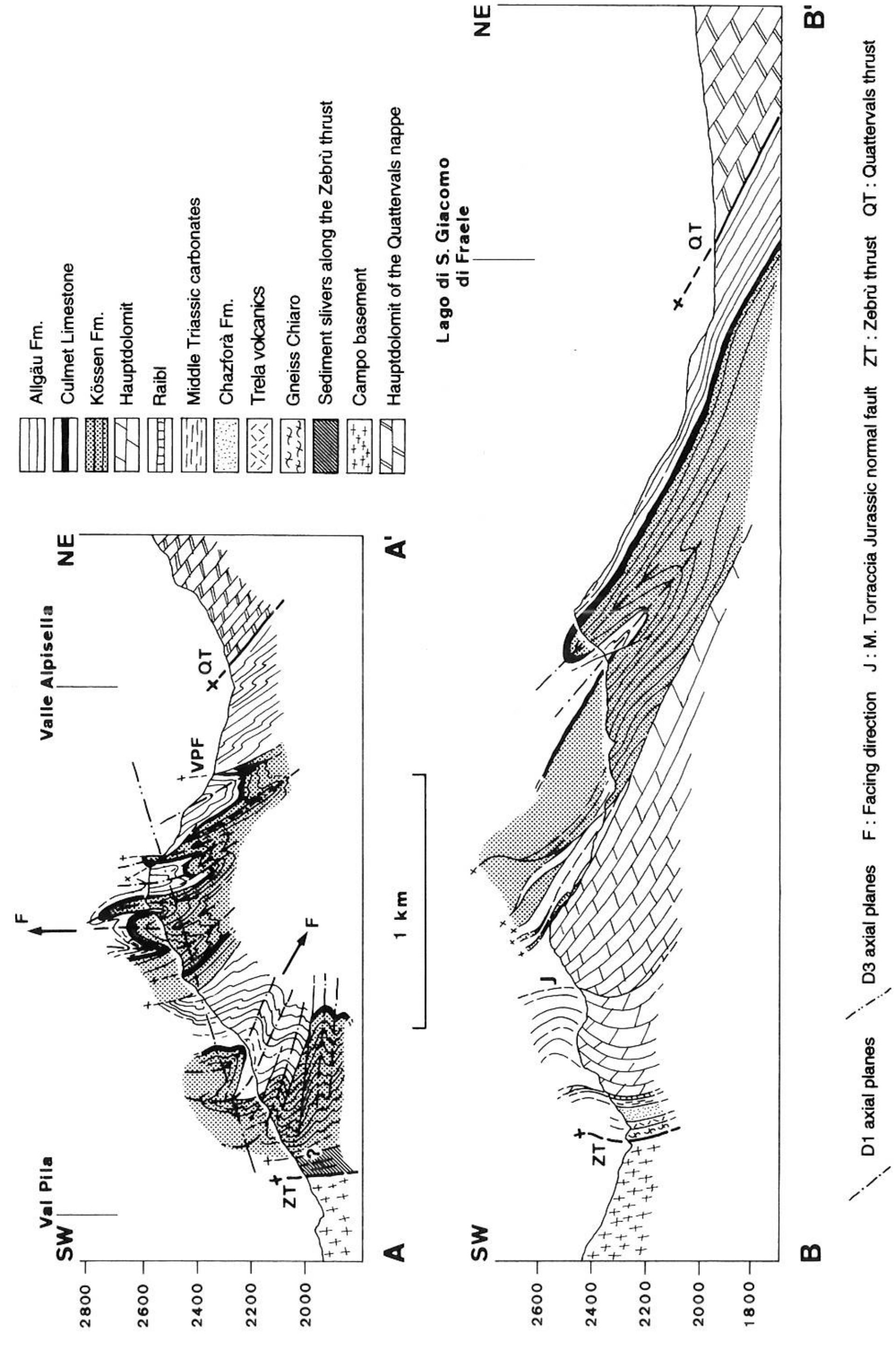
Fig. 12. Stereographic projections, equal area projection, lower hemisphere: a) lineations from the Quattervals thrust mylonites (Valle Alpisella); b) lineations from quartz mylonites along the Zebrù thrust; c) stretching lineations from sediments of the Ortler nappe (Valle di Fraele); d) D1 fold axes and fold axial planes in the Valle Alpisella-M. Pettini area (only large scale folds).

More information about the geometry of D1 folds can be obtained from a geological cross section (Fig. 13a) perpendicular to the transport direction in the most strongly folded area of the Ortler nappe. In this section, folds with an upward facing direction as well as folds with downward facing directions can be recognized. If we remove the effects of the later (D3) folding and place the fold axial planes into a subhorizontal attitude, the same D1 folds now appear to face southwest and northeast. This suggests again that during D1 deformation fold axes were rotated in the transport direction, some clockwise (the now northeast facing) and some others anticlockwise (the southwest facing ones), producing sheath-like geometry folds.

A very important feature of D1 deformation is the reactivation of the Monte Torraccia normal fault and the development of the Val Pila fault. We will discuss these topics separately later.

D2 and D4 phases

These phases, well documented in the Austroalpine nappes northwest of the Engadine Line (Froitzheim et al., in press), are not observed in the study area.


SW
NE
A
A'
Val Pila
Valle Alpisella
ZT
VPF
QT
F
F
?
1 km
2800
2600
2400
2200
2000
SW
NE
B
B'
Lago di S. Giacomo di Fraele
J
ZT
QT
2600
2400
2200
2000
1800
Allgäu Fm.
Culmet Limestone
Kössen Fm.
Hauptdolomit
Raibl
Middle Triassic carbonates
Chazforà Fm.
Trela volcanics
Gneiss Chiaro
Sediment slivers along the Zebrù thrust
Campo basement
Hauptdolomit of the Quattervals nappe
D1 axial planes
D3 axial planes
F : Facing direction
J : M. Torraccia Jurassic normal fault
ZT : Zebrù thrust
QT : Quattervals thrust

D3 phase

During later folding, kilometre-scale open folds formed, with differently dipping axial planes and westnorthwest – eastsoutheast oriented fold axes; an axial plane cleavage is rarely developed. This phase is recorded in the whole Austroalpine area and can be demonstrated to be the third deformation phase in the Ela nappe (Froitzheim 1992; Froitzheim et al. 1994). In our area, it did not produce strong deformation, but is only responsible for the general north dip of the entire Ortler nappe, from the Engadine valley to the Ortler-Königspitze (Gran Zebrù) massiv. Today the near parallelism between the D1 stretching lineation and D3 fold axis provides an opportunity to observe an east – west geological cross section of the Ortler nappe in map view, almost parallel to the transport direction.

The Oligocene magmatism in the Ortler massiv may constrain the timing of the deformation history. D3 folds in the Ortler nappe were here intruded by apophyses and dykes of mafic to intermediate composition and calc-alkaline affinity at around 31 Ma (Argenton et al. 1980; Dal Piaz et al. 1988).

b. Reactivation of the M. Torraccia normal fault

Normal faults can easily be reactivated during compression if the fault plane dips against the shortening direction and if the fault plane strikes perpendicular to the shortening direction (Etheridge 1986). As we have seen before, in the Ortler nappe a major east-dipping synsedimentary normal fault is preserved (Monte Torraccia normal fault), and D1 alpine deformation produced an east-west shortening with a top-to-the westnorthwest sense of movements. The normal fault is therefore properly oriented to be reactivated during the first Alpine deformation phase.

From a close inspection of the geological map some evidences for reactivation may be found:

a) the map view distribution of the redeposited sediments in the Allgäu Formation (Fig. 7) shows that they are now located further northwest with respect to the M. Torraccia Jurassic fault plane;
b) the contact Hauptdolomit/Kössen Formation immediately east of the Jurassic normal fault (in the hangingwall), though tectonic, is in a higher position than the same contact west of the normal fault (footwall);
c) west of Cima doscopa slivers of Gneiss Chiaro ("GC" in the geological map (Plate 1) and in Fig. 15c) are found between Hauptdolomit and the Middle Triassic carbonates along the normal fault;
d) basement rock slivers of the Campo nappe (Filladi di Bormio) occur between Gneiss Chiaro and Hauptdolomit south of Cima Doscopa;
e) southeast of Cima Doscopa intense mylonitized basement rocks and minor Middle Triassic carbonates occur along an Alpine thrust in the Hauptdolomit ("b" in the geological map and in Fig. 15c).

Fig. 13. Geological cross sections through the study area. See geological map in Plate 1 for location.

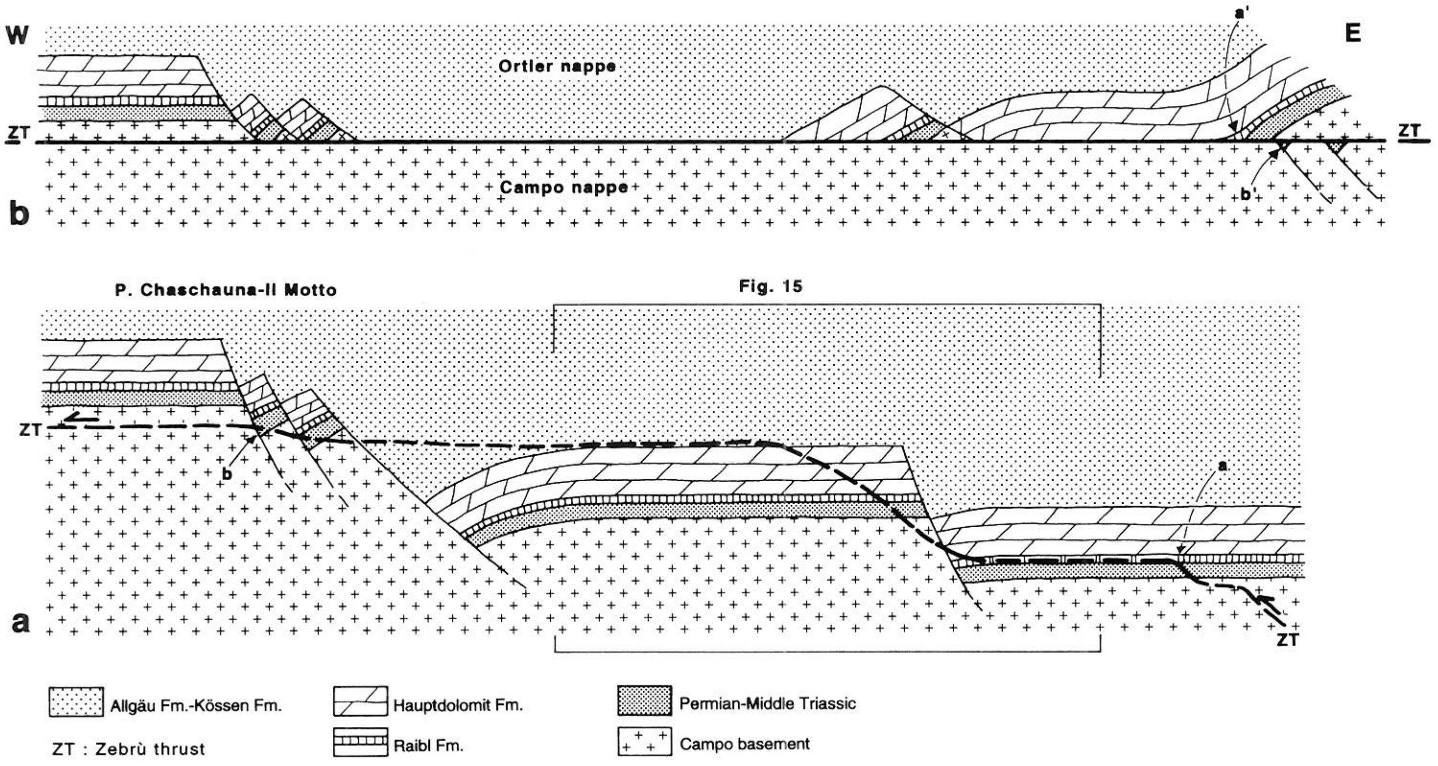


Fig. 14. "Younger-on-older" relationship along the Zebrù thrust.
a) The Zebrù thrust plane (dashed) runs at the base of the Hauptdolomit Formation in the eastern area, interferes with Jurassic normal faults and runs in basement rocks in the western area.
b) After west-thrusting sediments are directly emplaced above basement rocks originally located in a more westerly position (a–a' and b–b' indicate same points before and after thrusting).

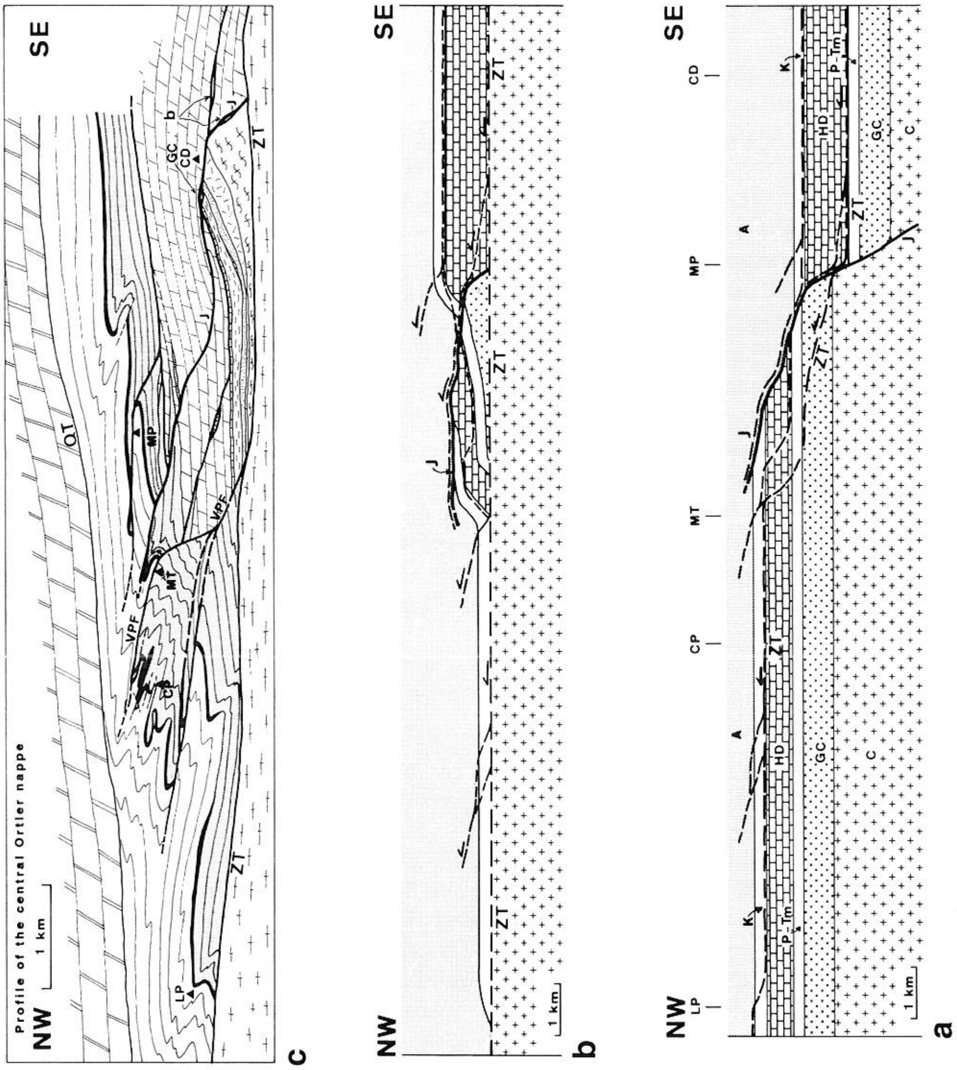


Fig. 15. a) Reconstruction at the end of Jurassic. Dashed are D1 Alpine thrust planes. Horizontal and vertical scale are equal. A = Allgäu Fm. (Lias), C = Campo nappe, GC = Gneiss Chiaro, HD = Hauptdolomit Fm. (Norian), K = Kössen Fm. (Rhaetian), P-Tm = Permian-Middle Triassic sediments. Note that b) and c) have a different scale than a). b) Schematic reconstruction after W-thrusting along the Zebrù thrust and before reactivation of the Monte Torraccia normal fault. c) Profile of the central Ortler nappe, legend as in Figure 13. The profile is constructed following the recipes of Ramsay & Huber (1987, p. 368), the profile plane strikes north 120° and plunges 45° toward southwest. b = basement rocks (mostly Filladi di Bormio of the Campo nappe), CD = Cima Doscopa, CP = Cima di Pozzin, GC = Gneiss Chiaro, J = Monte Torraccia Jurassic normal fault, LP = La Parè, MP = Monte Pettini, MT = Monte Torraccia, QT = Quattervals thrust, VPF = Val Pila fault, ZT = Zebrù thrust.

Such a situation, with lenses of older rocks between younger rocks cannot be produced by a single extensional or thrusting event. A combination of both is needed.

In Figure 15a the situation at the end of Jurassic extension based on the profile of Figure 15c is outlined. The reconstruction is schematic because a few simplifications were necessarily introduced during restoration: the fold axes are not everywhere perpendicular to the profile plane, only line lenght balancing is taken into account and any internal deformation of rocks is neglected. From this reconstruction we can see that the hanging wall of the Monte Torraccia normal fault was first vertically downfaulted for 0.8 km at the end of the Jurassic extension. During Alpine compression this fault was reactivated and the hangingwall was thrust westward along the same fault plane for a distance of at least 3 km (compare Fig. 15a and Fig. 15c). During reactivation, part of the footwall block did not remain fixed, but also suffered west-transport along a footwall shortcut (Hayward & Graham 1989; McClay & Buchanan 1992). The major floor thrust, the so called Zebrù thrust, runs at the base of the Hauptdolomit Formation in the eastern area (Cima Doscopa area). It cuts the Monte Torraccia normal fault ramping up westwards into the Campo basement and into the Gneiss Chiaro, which were in a topographically higher position due to the Liassic faulting. Then it climbs into the Permian-Middle Triassic sediments and finally cuts across the Hauptdolomit Formation in the Monte Torraccia area. This thrust continues further westwards with a flat geometry in the Kössen Formation. It ramps again at La Parè where it cuts the Triassic/Jurassic boundary (Culmet limestone) (Fig. 15a).

Immediately westwards and outside of the study area the Zebrù thrust plane interferes again with Jurassic normal faults: the Il Motto normal fault and the faults of the Piz Chaschauna area (Fig. 14). All these faults are also east-dipping normal faults. This implies again that the Zebrù thrust crosscuts Mesozoic fault planes and continues in the basement rocks of the footwall (the eastern termination of a horst), analoguous to what happened in the Monte Torraccia normal fault. If the throw of the Mesozoic normal faults is great enough the Zebrù thrust plane runs thoroughly within basement rock and does not ramps into the overlying sediments for a considerable distance. With this thrust geometry the sediments of the central parts of the Ortler nappe are emplaced during west-thrusting above basement rocks previously located in a more westerly position. The resulting geometry is reported in Figure 15b and sketched in Figure 14b.

During later thrusting, reactivation of the Monte Torraccia normal fault also took place. This interpretation is based on the occurrence of mylonitic basement and subordinate Permian-Middle Triassic rocks southeast of Cima Doscopa, along a thrust plane in the Hauptdolomit Formation. This thrust plane continues westward and runs along the Monte Torraccia normal fault. The presence of basement rocks in this position implies that the Hauptdolomit of the hanging wall block was juxtaposed against basement rocks before being thrust towards west along this thrust plane and the Monte Torraccia normal fault (Fig. 15b).

We may therefore distinguish two stages of deformation during D1: a first one (D1a) with most of the activity along the Zebrù thrust and a second one (D1b) with reactivation of the Monte Torraccia normal fault. It is difficult now to establish when the folding event occurred. We argued before that folding is contemporaenous with thrusting and mylonite formation along the Quattervals thrust. From regional considerations it is also proposed (Conti 1992) that movements along the Quattervals thrust postdate activity along the Zebrù thrust. Therefore we tentatively suggest that most of the folding developed during the second stage of deformation (D1b), together with the reactivation of the Monte Torraccia Jurassic normal fault and the emplacement of the Quattervals nappe.

It is also evident from Figure 15b that the Hauptdolomit Formation of the Ortler nappe wedges out to the west in the Monte Torraccia area due to the ramp geometry of the Zebrù thrust plane. Immediately westwards, a large volume of Kössen Formation is preserved, possibly because the Zebrù thrust plane runs here along a flat at the Hauptdolomit/Kössen boundary.

Another peculiar feature of the Monte Torraccia area remains to be discussed, the so called Val Pila fault (VPF in the geological map, Plate 1, Fig. 7). This fault has a paradoxe geometry and its nature is still a matter of discussion. It strikes northwest-southeast and shows a subvertical attitude, northeast-dipping in the northern segment (Valle Alpisella) and southwest-dipping in the southern part (Val Pila). Since the D1 folds axial planes in this area are also vertical (Fig. 13a) it is likely that the Val Pila fault also aquired this attitude later due to D3 deformation. The northeast block therefore represents the former hanging wall of this fault and the southwest block the footwall. The nature of the fault changes from northwest to southeast: in Valle Alpisella (in the northwest), the Allgäu Formation is in the hanging wall and the Kössen Formation is lying in the footwall (i.e. a typical normal fault geometry). In Val Pila (to the southeast) the Hauptdolomit rests on the Kössen Fm. and a thrust geometry can be proposed here (see Fig. 15c and Plate 1). Another problem is the exact age of this fault. A Jurassic age can be excluded because no resediments where found in the Allgäu Formation immediately east of the fault and because the fault plane cuts a D1 fold axial plane southeast of Monte Torraccia (Fig. 7). Later D2, D3 or D4 faulting can also be excluded because the Val Pila fault does not dissect the Zebrù thrust or the Quattervals thrust.

Based on all the evidence, we speculatively propose a two-phase activity along the Val Pila fault related to D1 (Fig. 16). Thrusting of Hauptdolomit onto the Kössen Formation occurred first (Fig. 16a), together with intense folding of the sediments, followed by Alpine normal faulting (Fig. 16b). In Figure 15a we can see that the thickness of the entire Ortler nappe decreases from east to west, confined between the Quattervals and the Campo units. This thickness reduction could be related with the emplacement of the rigid Hauptdolomit of the Quattervals nappe above the Kössen and Allgäu Formations of the Ortler nappe and achieved by west-thrusting and folding in the Cima Pozzin area and more or less contemporaneous east-directed extensional movements along the Val Pila fault.

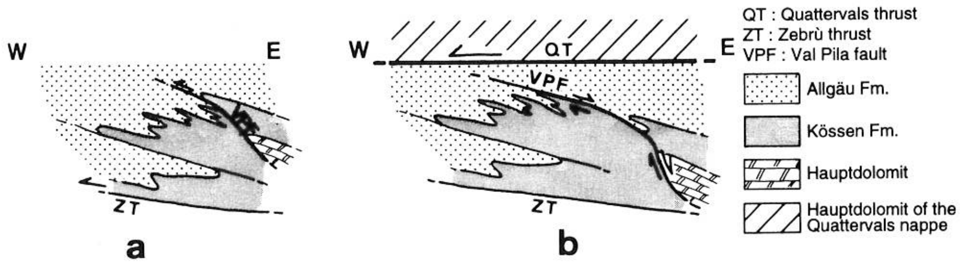


Fig. 16. Sketch showing activity along the Val Pila fault. a) Thrusting contemporaneous with folding; b) normal faulting during west-thrusting of the Quattervals nappe.

5. Conclusions

Fault-scarp related resediments in the Trupchun Beds of the Allgäu Formation in the area between Livigno and Valle di Fraele document Early Jurassic tectonic activity in the central part of the Ortler nappe. The resediments consist of breccias, conglomerates and calcarenites. New findings of ammonites indicate that the resediments accumulated in the Late Hettangian. The depositional geometry of the resediments is related to normal faulting along the east-dipping M. Torraccia normal fault that can be followed in the field from M. Torraccia to Cima Doscopa over a distance of more than 5 km.

The Jurassic age for the activity along this normal fault may be inferred from the observation that:

a) the M. Torraccia normal fault and the related unconformity are folded during D1 Alpine deformation,
b) the present day distribution of the resediments in map view indicates Alpine west-northwest-thrusting and reactivation of a pre-existing normal fault,
c) basement rock slivers found along the fault between younger rocks require a normal faulting phase before Alpine reactivation.

During D1 Alpine deformation westnorthwest-thrusting of the Ortler nappe above the Campo nappe and thrusting of the Quattervals nappe onto the Ortler nappe took place. Nappe emplacement was accompanied by folding, mylonite formation, and reactivated the Monte Torraccia Jurassic normal fault, cutting locally across basement and Middle Triassic sedments. Geometrical considerations led us to distinguish an earlier thrusting phase (D1a) from a later one (D1b) during which most of the reactivation of the normal fault took place. Late Alpine folding (D3) does not significantly complicate D1 structures; nappe contacts and bedding are gently folded and are now in a north-dipping attitude.

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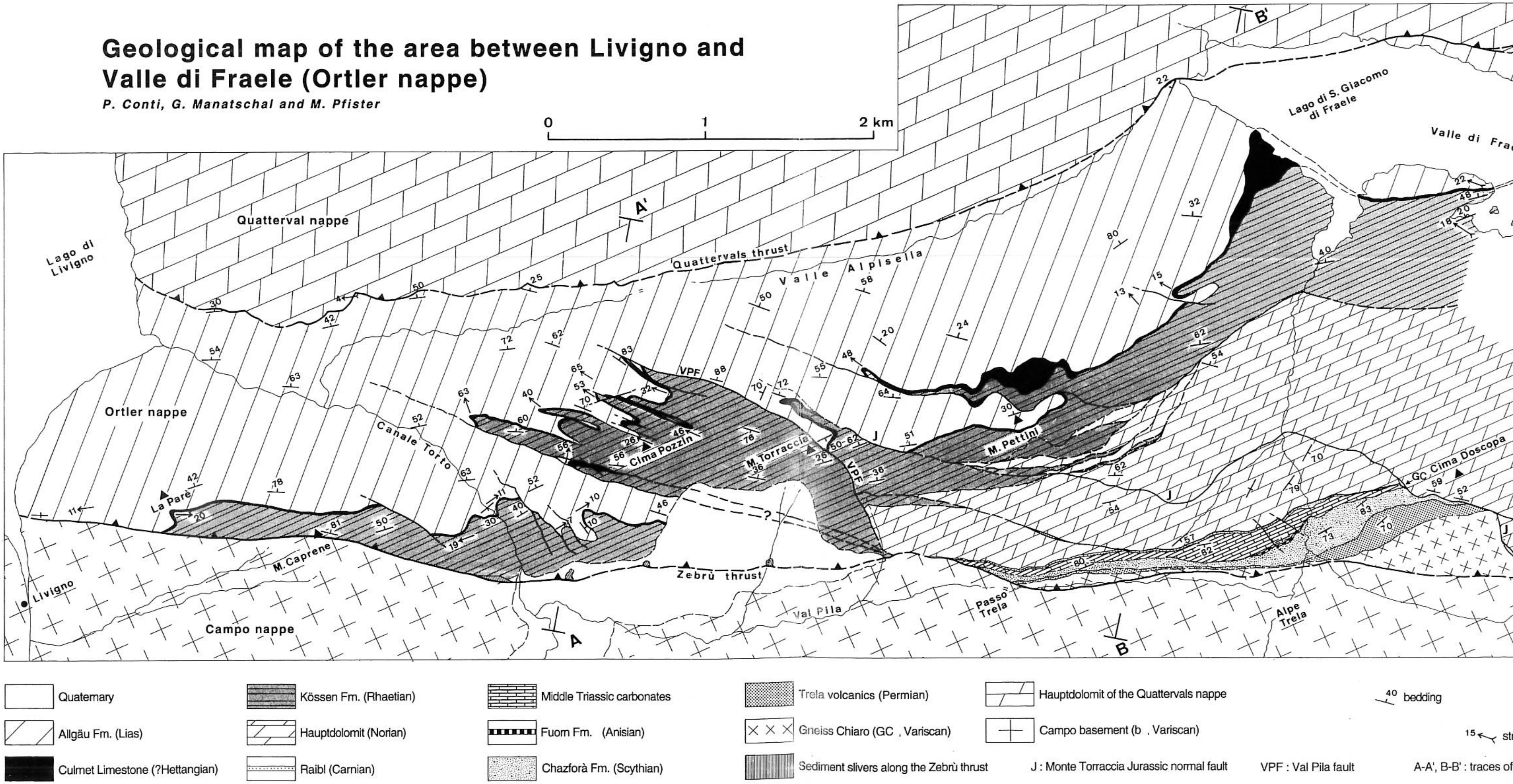
Geological map of the area between Livigno and Valle di Fraele (Ortler nappe)

P. Conti, G. Manatschal and M. Pfister



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