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Thrust imbrication and subsequent normal faulting in the western Austroalpine: The Arlui Fault and the Jaggl Mesozoic sediments (Ötztal Nappe, Vinschgau, Italy)

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Abstract

Jaggl is a mountain in the Upper Vinschgau, built up of Mesozoic sedimentary rocks and surrounded by crystalline basement rocks of the Ötztal Nappe. The Jaggl sedimentary rocks were originally interpreted as a remnant of the sedimentary cover of the Ötztal basement ("cover hypothesis"). Later, a different interpretation became prevalent, according to which the sedimentary rocks and a portion of the adjoining basement rocks represent a tectonic window into a deeper unit underlying the Ötztal Nappe ("window hypothesis"). A key role is played by the steeply southeast-dipping Arlui Fault along which the Jaggl Mesozoic rocks to the Southeast are in contact with Ötztal basement rocks to the Northwest. In the "window hypothesis", the displacement along the Arlui Fault should be southeast-side-up, whereas in the "cover hypothesis", it should be southeast-side-down. Our study of ductile (greenschist facies) to brittle fault rocks along the Arlui Fault yielded exclusively evidence for southeast-side-down, i.e. normal faulting. In addition, we identified the prolongation of the Arlui Fault towards northeast, represented by a top-southeast, greenschist-facies mylonite zone within the amphibolite-facies Ötztal basement. The Arlui Normal Fault belongs to the system of normal faults that overprinted the Austroalpine nappe stack during the Late Cretaceous, the Jaggl rocks are a downthrown part of the cover of the Ötztal Nappe, and the Jaggl Window does not exist.

1. Introduction

This article deals with the tectonics of the Ötztal Nappe, one of the Austroalpine Nappes. The Austroalpine is divided into a belt of mainly Mesozoic cover nappes to the North (Northern Calcareous Alps) and a belt of nappes comprising both Variscan basement and Permian to Mesozoic cover, to the South (Central Austroalpine Nappes; Fig. 1). The latter are again subdivided into the Lower Central Austroalpine, including the Ötztal Nappe, and the Upper Central Austroalpine (Janák et al., 2004). In addition, Lower Austroalpine Nappes occur locally along the base of the Austroalpine thrust edifice.

Schmid et al. (2004) suggested a more detailed subdivision of the Central Austroalpine, not just into Upper and Lower Central Austroalpine but into five nappe systems (from top to bottom: Grauwackenzone, Drauzug-Gurktal, Ötztal-Bundschuh, Koralpe-Wölz, Silvretta-Seckau). This involved cutting the Ötztal Nappe, formerly interpreted as one tectonic unit (e.g. Schmidegg, 1964) into two tectonic units belonging to two different nappe systems: the structurally higher Ötztal Complex s.str. belonging to the Ötztal-Bundschuh Nappe System, and the structurally deeper Texel Complex (located east of the area shown in Fig. 2) belonging to the Koralpe-Wölz Nappe System.

Figure 1: Tectonic sketch map of the Eastern Alps. Rectangle indicates location of Figure 2. Abbreviations: B: Bajuvarikum; BM: Brenner Mesozoic; C: Campo Nappe; E: Engadine Window; GZ: Grauwacke Zone; Ö: Ötztal Nappe; T: Tirolikum. After Janák et al. (2004), modified.

However, Klug and Froitzheim (2021) as well as Thöni (2024) showed that such a tectonic separation between Ötztal and Texel complexes does not exist. Therefore, we prefer, for the purpose of this article, to use the tectonic subdivision of Janák et al. (2004).

The Lower Central Austroalpine Nappes were imbricated by west- to northwest-directed thrusting during the Cretaceous (Trupchun Phase; ~100 to 80 Ma; Froitzheim et al., 1994), in connection with southeast-directed, intra-continental subduction culminating at 100 to 90 Ma (Thöni and Jagoutz, 1992; Thöni et al., 2008; Miladinova et al., 2021). During the Late Cretaceous, the Austroalpine nappe stack was stretched and dissected by predominantly east- to southeast-dipping, high- and low-angle normal faults (Ducan-Ela Phase; ~80 to 67 Ma; Froitzheim et al., 1994). Only after this, during the Cenozoic, the Austroalpine was emplaced as one big thrust mass northward over the Penninic and Helvetic units.

The study area is located in the western part of the Ötztal Nappe (Fig. 2), a major thrust sheet of the Lower Central Austroalpine. The Ötztal Nappe mainly comprises Variscan basement rocks. Remnants of its Permian to Mesozoic cover are found in the eastern part of the nappe (Brenner Mesozoic), and, arguably, as a small outlier forming the mountain Jaggl (also called Jackel, Endkopf, or Cima Termine) close to the western border of the nappe. In addition, Triassic sedimentary rocks at Piz Lad, NW of Jaggl, are interpreted as remnants of the Ötztal cover (Fig. 2; Froitzheim et al., 1997). The present article deals with the tectonic position and emplacement of the Jaggl Permian to Mesozoic rocks.

Lachmann (1908) published the first detailed study of the geology of Jaggl and its surroundings. His interpretation of the tectonic evolution is as follows: A first phase of west-directed thrusting of the sedimentary rocks was followed by northwest-vergent folding. In his view, the Jaggl sediments represent west- to northwestward displaced cover of the Ötztal Basement. Hammer (1911) provided a detailed map, profiles, field sketches and description of Jaggl and its surroundings and offered two alternative tectonic interpretations: the "cover hypothesis" and, in addition, the "window hypothesis" which Otto Ampferer had suggested to him. The "window hypothesis" was firmly established by Hess (1962). He pointed out that the Permian to Mesozoic sedimentary succession of Jaggl is very similar to the succession of the northern S-charl Nappe, the next-deeper tectonic unit underlying the Ötztal Nappe and exposed west of it. He also found strong similarities between the internal tectonic structure of Jaggl and the S-charl Nappe. He based the "window hypothesis" mainly on these similarities. As the oldest Jaggl sediments (Permian Chazforà Formation) rest

Figure 2: Tectonic map of the western Ötztal Nappe and surrounding units. The Jaggl sediment succession is treated as a remnant of the Ötztal Nappe cover and the Arlui Fault as a normal fault, according to the results of the present study. Grid lines and numbers refer to the Swiss coordinate system. Geology after Bundesamt für Wasser und Geologie (2005), Froitzheim et al. (1997), Montemagni et al. (2023), and new results.

with a sedimentary contact on basement orthogneiss to the East (Plawenn Orthogneiss), the latter must also be part of the Jaggl Window and the basal thrust of the Ötztal Nappe must be located between the Plawenn Orthogneiss and other basement rocks of the Ötztal Nappe. He interpreted the Arlui Fault at the northwest border of the Jaggl sedimentary rocks as the overturned basal thrust of the Ötztal Nappe, now steeply dipping southeast (Fig. 3a). Thöni (1973) described previously unnoticed outcrops of Permian to Mesozoic rocks northeast of Jaggl, on the northern side of the Langtaufers Valley between Pedross and Padöll (Fig. 2). These rocks form the northeastward extension of the Jaggl sedimentary rocks. North of and upslope from these outcrops, gneiss and schist of the Ötztal basement crop out. The basement-sediment contact itself is not exposed. Thöni (1973) assumed that the basement rocks overly the sedimentary rocks along a thrust contact, thereby supporting the window hypothesis.

Froitzheim et al. (1997), in contrast, argued that the Jaggl rocks are a remnant of the Ötztal cover thrown down towards southeast along the Arlui Fault (Fig. 3b). They found top-southeast shear-sense indicators along the Arlui Fault and interpreted it as a high-angle normal fault connected with and dissecting the hanging wall of the low-angle Schlinig normal fault. The latter forms the western border of the Ötztal Nappe in this area.

Thöni (2012) described the regional geology in terms of the "window hypothesis". He showed a cross section (see Fig. 14 in Thöni, 2012) where the Arlui Fault is not the overturned basal thrust of the Ötztal basement but a post-nappe reverse fault bringing the Ötztal basal thrust back to the surface, leading to the formation of the window (Fig. 3c). Thöni's cross section suggests that the reverse faulting along the Arlui Fault was overprinted by minor normal displacement.

In order to clarify the structure of the Jaggl area, we newly mapped the Permian-Mesozoic rocks and their surroundings and collected fault rocks from the Arlui Fault. We found only top-southeast shear sense along the Arlui Fault and no evidence for a top-northwest movement as predicted by the two variants of the "window hypothesis" (Hess, 1962; Thöni, 2012). In addition, we followed the intra-basement continuation of the Arlui Fault towards east up to the Italian-Austrian border.

Figure 3: Different tectonic interpretations of the Jaggl sedimentary rocks. **(a)** Hess (1962) interpreted the Jaggl sediments and the Plawenn Gneiss as a window into the S-charl Nappe, and the Arlui Fault as the inverted thrust of the Ötztal Nappe over the S-charl Nappe. **(b)** Froitzheim (1997) interpreted the Jaggl sediments as a remnant of the Ötztal cover, the Plawenn Gneiss as belonging to the Ötztal basement, and the Arlui Fault as a post-nappe normal fault connected with the low-angle Schlinig Normal Fault. **(c)** Thöni (2012) again interpreted the Jaggl sediments and the Plawenn Gneiss as a window, but the Arlui Fault as an out-of-sequence thrust which lifted the rocks of the Jaggl window up to the surface. Note that (a) and (c) require southeast-side-up, i.e. reverse sense of displacement along the Arlui Fault, whereas (b) requires southeast-side-down, i.e. normal sense of displacement.

2. Regional geologic framework

The geology and geochronology of the Ötztal Nappe in the area around Jaggl are well known due to many detailed studies (Lachmann, 1908; Hammer, 1911; Hess, 1962; Thöni, 1973, 1980; Richter and Zinkernagel, 1975; van Gool, 1985; Schmid and Haas, 1989; Froitzheim et al., 1997). The western border of the nappe is formed by the shallowly east-dipping Schlinig Fault along which metamorphic basement of the Ötztal nappe overlies the Permian to Mesozoic sedimentary cover and the Variscan basement (Sesvenna Basement) of the S-charl Nappe. Although the Schlinig Fault appears as a typical top-west overthrust (Schmid and Haas, 1989), it is indeed a top-east to top-southeast low-angle normal fault throwing down the basement of a previously emplaced higher nappe, the Ötztal Nappe, onto a deeper nappe, the S-charl Nappe (Froitzheim et al., 1997). In the small Rojen Window west of the Reschen Lake, sedimentary rocks of the S-charl Nappe are exposed due to erosion through the Schlinig Fault. In the South near Mals, the Schlinig Fault turns around and continues in a northeast-southwest direction into Val Müstair where it is known as the Gallo Fault. In the North near Nauders, the Schlinig Fault enters the Ötztal Nappe as an intra-basement fault. Its further continuation towards northeast has not yet been studied. The southern border of the Ötztal Nappe is the Vinschgau Shear Zone, a thick zone of mylonites with a predominantly north-dipping foliation, east-west lineation and predominantly top-west shear sense (Schmid and Haas, 1989; Montemagni et al., 2023).

In a different interpretation, some authors have assumed that the Schlinig Fault continues into the Vinschgau Shear Zone (Schmid and Haas, 1989; Krenn et al., 2011; Pomella et al., 2016). We do not follow this view because the shear sense of mylonites in the Vinschgau Shear Zone (dominantly top-west: Schmid and Haas, 1989; Montemagni et al., 2023) is opposite to the one along the Schlinig Fault (top-east to -southeast; Froitzheim et al., 1997). The footwall of the Vinschgau Shear Zone, south of the Vinschgau Valley, is formed by the Campo Nappe. On the other hand, the Matsch Unit, an outlier of rocks strikingly similar to the Campo Nappe, occurs north of the Vinschgau Shear Zone on top of the Ötztal basement (Habler et al., 2009). Pomella et al. (2022) reported similarities between the Matsch Unit and a tectonic unit bordering the Ötztal Nappe to the southeast (Schenna Unit) which belongs to the Upper Central Austroalpine. Hence, the Matsch Unit may represent a far-travelled nappe and not just a subunit of the Ötztal Nappe.

The basement of the Ötztal Nappe is dominated by paragneiss and mica schist, granitoid orthogneiss (often from Ordovician protoliths; e.g., Klug et al., 2025) and metabasic rocks. Variscan eclogite with an age between 370 and 340 Ma occurs in the central part of the Ötztal Nappe

(Miller and Thöni, 1995). The pressure peak was followed by widespread amphibolite-facies equilibration. Staurolite-kyanite-sillimanite-andalusite gneiss and garnet mica schist in the Upper Langtaufers Valley (Melag Valley), a few kilometers northeast of Jaggl, reflect conditions of 0.58–0.75 GPa, 570–640 °C (Tropper and Hoinkes, 1996). Sm-Nd dating yielded ages between ~343 and ~319 Ma for this metamorphic stage (Thöni, 2024). The grade of Alpine metamorphism in the Ötztal Nappe decreases from SE to NW (Purtscheller and Rammlmair, 1982; Raso et al., 2025). In the southeastern part (Texel Complex) eclogite facies was reached in the Alpine cycle again, followed by amphibolite facies (Habler et al., 2006). In the Jaggl area, Raso et al. (2025) determined Alpine metamorphic conditions on a sample from a post-Variscan, pre-Alpine mafic dyke in the Ötztal basement, collected immediately northwest of the Arlui Fault between Pedross and Padöll (Fig. 2). Using the THERMOCALC modelling software, they derived conditions of 0.34±0.13 GPa, 423±41 °C for the Alpine metamorphism of this sample.

The Alpine temperature peak occurred at ~90 to 85 Ma (Thöni, 1980; Thöni and Hoinkes, 1987). Hölzer et al. (2024) used low-T thermochronology and thermokinematic modelling to reconstruct a three-phase exhumation history for the Ötztal Nappe, including rapid exhumation in the Cretaceous until ~70 Ma, followed by slow or almost no exhumation between ~70 and ~16 Ma, and again rapid exhumation after ~16 Ma. Evidence for Cretaceous exhumation and cooling was also found in a combined structural/fission-track study by Fügenschuh et al. (2000) close to the eastern border of the Ötztal Nappe. It resulted from unroofing of the footwall of a southeast-dipping low-angle fault (the Steinach Normal Fault of Klug and Froitzheim, 2021).

3. Stratigraphy of Jaggl

In the following, we will use the formation names for the Permian and Triassic sedimentary rocks in the Austroalpine Nappes of eastern Switzerland as defined in Furrer (1985). The oldest post-Variscan rocks of the Jaggl area are felsic volcanic rocks unaffected by Variscan metamorphism. Two dykes of these rocks occur within gneiss of the Ötztal Nappe at the entrance of the Rauchtal, already described by Hammer (1911). Overprinted by mylonitic deformation, similar volcanic rocks occur as a thin layer immediately below the Arlui Fault, between Variscan basement to the Northwest and various Permian to Triassic sedimentary rocks to the Southeast. In the Austroalpine Nappes of eastern Switzerland, such volcanic rocks are frequently found between the basement and the Permian conglomerates and arkoses of the Chazforà Formation. The age is Early Permian (Furrer, 1985).

The volcanics occur only on the northwest side of Jaggl; on the eastern side, the Permian conglomerates and arkoses of the Chazforà Formation (termed Verrucano in Hammer, 1911) rest directly with a depositional contact on the Plawenn Orthogneiss ("Plawenner Granit" of Hess, 1962). The Chazforà Formation is overlain by quartz sandstones with carbonatic layers, the Fuorn Formation (termed Buntsandstein in Hammer, 1911). This is followed by the Ducan Formation (Anisian), comprising nodular limestone, dolomite with chert nodules, and dark dolomite with crinoids (Encrinitendolomit of Hammer, 1911). This is overlain by the S-charl Formation (Anisian to Ladinian), comprising Rauwacke, i.e. a cavernous and brecciated calcite rock, and grey to pink, often mylonitic limestone and calcschist. Dolomites of the Vallatscha Formation follow above (Diploporendolomit of Hammer, 1911). These are Ladinian in age. The youngest sediment of the Jaggl Mesozoic is a several 100 meters thick succession of Rauwacke, belonging to the Raibl Group (Carnian).

4. Tectonic structure of Jaggl

The sedimentary rock succession of Jaggl has been deformed by thrusting and folding (Figs. 4, 5). The Chazforà and Fuorn formations on the eastern side were folded together with the basal unconformity and the uppermost part of the basement gneisses. The folds are tight to open and have a well-developed axial-plane cleavage. The axes trend NE-SW and the axial planes are mostly horizontal to shallowly southeast-dipping (Fig. 6a). The folds face northwest. The northwesternmost syncline (Marbeltal Syncline) is upright (Fig. 4). Complex folding of the Ducan Formation in the core of an anticline south of the summit of Jaggl (Fig. 5) probably resulted from progressive deformation during top-northwest shearing.

Within the Triassic sedimentary rocks, three subhorizontal thrust faults are exposed, stacked one on top of the other, each of them emplacing older on top of younger rocks. The lowermost thrust (TF1) brings Vallatscha Formation over Raibl Rauwacke, the middle thrust (TF2) S-charl Formation over Vallatscha, and the uppermost (TF3) brings Fuorn Formation over S-charl Formation. Mylonitic calcschist of the S-charl Formation along the middle thrust (TF2) displays a NW-SE stretching lineation; S-C structure indicates top-NW thrusting (Fig. 6b), i.e. in a direction normal to the trend of the above-mentioned folds. Therefore, it is likely that the folds and the thrusts formed together in a kinematic framework of NW-SE shortening with a NW vergence. The contacts between the Vallatscha dolomite and the other formations are generally discordant with respect to the bedding of the dolomite. This may be explained by the brittle behaviour of the dolomite which did not allow it to be folded together with the other formations; it rather broke up into large blocks during the folding.

Another shallowly dipping fault (NF1) lies below the lowermost thrust. Along this fault, however, younger rocks (Raibl Rauwacke) rest on older rocks (Vallatscha Formation). A steeply southeast-dipping fault (NF2; orientation 132/73) branches from this fault down into the Vallatscha dolomite (Fig. 7a). The asymmetry of drag folding along this fault indicates normal (southeast-side-

Figure 4: **(a)** Geological map and **(b)** cross section of Jaggl. Schmidt nets (lower hemisphere) show orientation of fault plane (red great circle), foliation (black great circles) and stretching lineation (dots) from the following locations: (1) Rauchtal; (2) Arlujer Wald; (3) Marbeltal; (4) Vordere Karlesspitze.

Figure 5: (a) Photograph and **(b)** sketch of the southern slope of Jaggl, showing thrusts (TF1, 2, 3) and normal folds (NF1, 2). Colours in the sketch are the same as in Figure 4.

down) displacement (Fig. 7b). The younger-on-older relation along NF1 and the drag folding along NF2 suggest that NF1 and NF2 represent two kinematically connected top-southeast normal faults.

5. The Arlui Fault

The Arlui Fault is mostly hidden under Quaternary sediments. In the Upper Vinschgau Valley, it is hidden under Quaternary fan deposits (Fig. 2). At the foot of Jaggl, the fault is well exposed in two small gorges, Rauchtal and Marbeltal (Fig. 4). Between the two valleys, outcrops of the fault rocks exist in the Arlujer Wald. From Marbeltal towards northeast, the fault disappears again under Quaternary valley fill of the Langtaufers Valley. It runs for some distance along the north side of this valley (between Pedross and Padöll; Fig. 2) where its trace is constrained by outcrops of Mesozoic sediments and Ötztal basement rocks but the fault itself is not exposed. Further east, it returns to the valley floor. Where the Langtaufers Valley turns to the southeast, the fault continues straight in an east-northeast direction in the small tributary valley Karlestal and finally reaches the border ridge between Italy and Austria a short distance north of the summit of Vordere Karlesspitze.

5.1. Rauchtal

Rauchtal is a short gorge at the foot of Jaggl, leading from the shore of the Reschen Lake towards east to the base of a rock cliff formed by dolomite of the Vallatscha Formation. At the entrance of the gorge, a felsic volcanic rock crops out, showing a porphyric texture with plagioclase, quartz, and minor amphibole phenocrysts. The quartz phenocrysts display resorption embayments (Fig. 8a). The rock does not show the Variscan schistosity of the

Figure 6: Alpine fold and thrust structures (Trupchun Phase) on the south side of Jaggl. **(a)** folds with axial planar cleavage in clastic sediments of the Chazforà Formation. Fold axes plunge northeast (055/22), axial plane dips east (084/30). Hammer for scale. Coordinates: 46°47′10.9″N, 10°34′18.3″E. **(b)** S-C-structure in mylonitic calcschist of the S-charl Formation (Anisian) at the base of the hanging wall of the middle thrust TF2, indicating top-NW shearing. Stretching lineation trends southeast-northwest (135/14). Diameter of coin is 2.2 cm. Coordinates: 46°47′15.3″N, 10°34′6.7″E.

Figure 7: **(a)** SE-dipping high-angle normal fault NF2 in dolomite of the Vallatscha Formation on the southwest side of Jaggl. Northwest is to the left. Coordinates: 46°47′13.8″N, 10°33′33.2″E. **(b)** drag folds deforming bedding planes in the hanging wall along the normal fault, indicating SE-side-down movement. Hammer for scale. Coordinates: 46°47′15.5″N, 10°33′34.8″E**.**

Figure 8: Outcrop and thin-section photographs from the Rauchtal. **(a)** Quartz phenocryst with resorption embayment in a felsic volcanic dyke, probably of Permian age, crosscutting the Variscan Ötztal basement at the entrance of the Rauchtal. Alpine deformation is represented by deformation bands (subhorizontal) and deformation lamellae (thin stripes dipping to the right) in the quartz phenocryst. Crossed polarizers. Coordinates: 46°47′47.9″N, 10°32′34.7″E. **(b)** Thin section photograph of brittle to ductile shear band (arrow) with sigmoidally deformed muscovite (blueish interference colour) in a retrograded paragneiss from the footwall of the Arlui Fault, few meters below the fault plane. Crossed polarizers. Coordinates: 46°47′49.4″N, 10°32′40.2″E. **(c)** Southeast-dipping brittle to ductile shear bands with sigmoidally deformed foliation in retrograded Ötztal Gneiss, in the footwall few meters below the Arlui Fault. The shear bands indicate top-southeast normal-fault movement. Diameter of coin is 2.2 cm. Coordinates: 46°47′49.6″N, 10°32′43.0″E. **(d)** Deformation in the hanging wall of the Arlui Fault. Dolomite of the Vallatscha Formation (Ladinian) is crosscut by a system of subsidiary normal faults synthetic to the main fault. The main fault is under the scree on the right. Outcrop is ~20 m high. Coordinates: 46°47′46.9″N, 10°32′42.3″E**.**

Ötztal basement and must therefore be post-Variscan, i.e. Late Carboniferous or younger. On the other hand, the rock shows some Alpine deformation, including deformation bands and deformation lamellae in the quartz phenocrysts (Fig. 8a). We infer an Early Permian age for these rocks because of their similarity to rhyolites and rhyodacites of the Early Permian Ruina Formation in the S-charl Nappe (Furrer, 1985). The Rauchtal outcrop belongs to two parallel, southwest-northeast-striking dykes in the Ötztal basement which were already mapped by Hammer (1911). Paragneiss follows up the gorge, increasingly affected by retrograde metamorphism (lower greenschist facies) and deformation when approaching the Arlui Fault. In its upper part, closest to the fault, the gneiss shows shear bands and sigmoidally deformed foliation indicating top-southeast, normal sense of shear (Fig. 8b, c). The paragneiss is followed by sericite-rich, phyllonitic mylonites derived from felsic volcanic rocks, with a thickness of eight meters, similar to the ones cropping out in the Arlujer Wald (see below). The foliation of these rocks dips southeast (105/32; 114/22) and the stretching lineation plunges southeast (153/21; 146/20). The Arlui Fault itself is covered by scree between these mylonites and the base of the dolomite cliff (Vallatscha Formation). The dolomite in the hanging wall is crosscut by subsidiary normal faults synthetic to the Arlui Fault, i.e., southeast-side-down (Fig. 8d).

5.2. Arlujer Wald

Sericite-rich, phyllonitic mylonites crop out in the footwall of the Arlui Fault along the forest road from Graun to Grauner Alpe. The foliation dips southeast (114/45) and the stretching lineation is parallel to dip. Shear bands with sigmoidally deformed foliation indicate top-southeast, normal sense of shear (Fig. 9a). Quartz porphyroclasts

Figure 9: Mylonite in the footwall of the Arlui Fault, few meters below the fault, in Arlujer Wald. The protolith is Permian volcanite. Coordinates: 46°48′03.7″N, 10°32′54.8″E. **(a)** Shear bands (vertical) and sigmoidally deformed foliation (dipping to the right), indicating dextral shear sense (southeast-side-down). Diameter of coin is 2.3 cm. **(b)** Magmatic quartz phenocryst with resorption embayment, now forming a porphyroclast in the fine-grained matrix. **(c)** σ-type porphyroclast of quartz indicating dextral (top southeast) shear sense. Foliation dips southeast (114/45); stretching lineation is parallel to dip. Thin section is oriented parallel to stretching lineation and perpendicular to foliation. **(d)** σ-type porphyroclast of plagioclase indicating dextral (top southeast) shear sense. Same orientation as in (c). All thin section photographs with crossed polarizers.

with resorption embayments testify for the volcanic origin of the rocks (Fig. 9b). Sigma-type porphyroclasts of quartz (Fig. 9c) and plagioclase (Fig. 9d) also indicate top-southeast, normal sense of shear.

Hammer (1911) already suggested that these rocks are deformed equivalents of the Permian volcanic rocks found as dykes within the basement rocks at the entrance of the Rauchtal. This is confirmed by the quartz crystals with resorption embayments found in both rocks. Consequently, these rocks are a special case of mylonite where the fine-grained matrix is not the product of recrystallization of a coarser-grained rock but was already present in the protolith, forming the fine-grained matrix of a porphyric volcanic rock. Nevertheless, the deformation resulted in σ-type porphyroclast systems developing from the original phenocrysts.

5.3. Marbeltal

In the Marbeltal, the fault plane of the Arlui Fault is exposed between mylonitized felsic volcanic rocks in the footwall, of the same type as in the Arlujer Wald, and brittlely deformed conglomerate and arkosic sandstone of the Chazforà Formation in the hanging wall (Fig. 10). The mylonite has southeast-dipping foliation (131/30) and stretching lineation plunging in the same direction. Abundant shear bands in the mylonite consistently indicate top-southeast sense of shear (Fig. 11a). This shear sense is confirmed by σ-type porphyroclasts of amphibole in thin section (Fig. 11b). The fault plane of the Arlui Fault dips southeast (149/59). The Chazforà Formation is followed by quartz sandstone of the Fuorn Formation and then by light-coloured dolomite, probably Vallatscha Formation. Another layer of Fuorn Formation follows above the dolomite and is in turn overlain by another dolomite along a sharp fault plane (orientation 141/52). Rauwacke of the Raibl Group follows above, with a thickness of several 100 meters. The distance between the top of the basement (Arlui Fault) and the base of the Raibl Group is only about 25 meters whereas this thickness is about 700 meters in the area of Jaggl. Therefore, the section must have been telescoped by subsidiary normal faults in the hanging wall of the Arlui Fault. The duplication of the Fuorn Formation may be explained by a thrust emplacing Fuorn Formation over dolomite before normal faulting took place.

Figure 10: Arlui Fault in the Marbeltal. The fault plane separates mylonite in the footwall from cataclastically deformed slivers of Permian to Middle Triassic sediments in the hanging wall. Duplication of the Fuorn Formation may be explained by a thrust which emplaced Fuorn Formation on top of the younger dolomite during thrust imbrication, before the normal faulting. The profile is about 30 meters long. Coordinates: 46°48′13.4″N, 10°33′19.7″E.

5.4. North side of Langtaufers Valley between Pedross and Padöll

Scattered outcrops of Permian to Mesozoic sediments are found in the northern slope of the Langtaufers Valley between Pedross and Padöll (Fig. 2), as described by Thöni (1973). These form a northeastward extension of the Jaggl sequence. Higher up the slope are outcrops of paragneiss belonging to the Ötztal basement. The contact itself is not exposed but its location is roughly constrained by the outcrops. The Ötztal paragneiss is locally mylonitic and retrograde in the lower greenschist facies. The foliation of the mylonites is variably oriented, possibly resulting from slope instability. The outcrop relations were interpreted by Thöni (1973) in terms of a thrust contact of Ötztal basement above the sedimentary rocks. However, a steeply southeast-dipping fault contact, steeper than the slope, would also be geometrically possible. We prefer the latter interpretation because the Arlui Fault dips steeply southeast both west of this area (Marbeltal) and again east of it (Karlestal).

5.5. Karlestal

East of Padöll, the Arlui Fault returns to the WSW-ENE oriented floor of the Langtaufers Valley and is hidden by Quaternary sediments. At Melag, the Langtaufers Valley makes a bend towards southeast but the SW-NE trend of the lower Langtaufers Valley is continued by a small tributary valley, the Karlestal, leading up to the border ridge between Italy and Austria which coincides with the main drainage divide of the Alps. A steeply south-southeast dipping fault zone is visible in the background of Karlestal crosscutting the summit pyramid of Vordere Karlesspitze (3230 m) (Fig. 12a). The rocks to both sides of the fault zone are amphibolite-facies paragneiss, partly with garnet and large kyanite crystals, and minor orthogneiss and amphibolite. Mylonites cropping out in the Karlestal at an altitude of 2800 m are part of this fault zone (Fig. 12b). The mylonites are derived from granitoid orthogneiss and exhibit a foliation dipping south to southeast (172/72) and a very well-developed stretching lineation plunging southeast (121/61; Fig. 12c). On surfaces parallel to the lineation and perpendicular to the foliation, shear bands indicate top-southeast, normal-sense mylonitic shearing (Fig. 12d). In thin section, S-C structure (Fig. 12e) confirms the top-southeast shear sense. Quartz microstructure is typical for dynamic recrystallization, with large, elongate relict grains and small recrystallized grains (Fig. 12f), indicating temperatures of more than 300 °C during deformation (Stipp et al., 2002).

The mylonites of this fault zone have a very similar orientation as the ones in the footwall of the Arlui Fault in the Jaggl area (Rauchtal and Marbeltal) and they share the same shear sense, top-southeast. Moreover, they oc-

Figure 11: Mylonitized volcanic rock ~6 meters below the fault plane of the Arlui Fault in the Marbeltal. Coordinates: 46°48′13.3″N, 10°33′19.6″E. **(a)** Shear bands (arrows) and sigmoidally deformed foliation indicating top-southeast, normal sense of shear. Foliation dips southeast (131/30); Stretching lineation is parallel to the dip direction of the foliation. Diameter of coin is 2.3 cm. **(b)** σ-type porphyroclast of amphibole in a thin section from the same outcrop, indicating the same sense of shear. Parallel polarizers.

cur in the exact prolongation of the Arlui Fault. Therefore, it can safely be assumed that the fault zone in the Karlestal represents the Arlui Fault within the basement of the Ötztal Nappe. The Arlui Fault probably continues on the other side of Vordere Karlesspitze into Austria (Kaunertal).

6. Discussion

The internal tectonic structure of the Jaggl Mesozoics displays northwest-directed thrusts (TF1, TF 2, and TF3) and extensional faults NF1, a low-angle normal fault, and NF2, a southeast-dipping high-angle normal fault. This is a very similar situation as in the S-charl Nappe (Froitzheim et al., 1997) and is most easily explained by top-northwest thrusting in the Trupchun Phase (~100–80 Ma; Froitzheim et al., 1997) followed by top-southeast normal faulting in the Ducan-Ela Phase (~80–67 Ma).

The Arlui Fault is a southeast-dipping normal fault as well. The normal-fault sense of displacement is supported by synthetic southeast-side-down normal faults in the hanging-wall dolomite in the Rauchtal (Fig. 8d), brittle to ductile shear band structure in Ötztal paragneiss in the Rauchtal (Fig. 8b, c), ductile mylonite with shear bands and σ-type porphyroclasts derived from Permian volcanics in the Rauchtal, Arlujer Wald and Marbeltal (Figs. 9, 10), and shear bands and C-S structure in orthogneiss mylonite in Karlestal (Fig. 12). In summary, structural evidence for a normal-fault character of the Arlui Fault is overwhelming. We found no evidence for a reverse movement along the Arlui Fault as would be required by the "Jaggl Window Hypothesis". Consequently, the Jaggl Mesozoics must be a remnant of the tectonically deformed cover of the Ötztal Nappe, downthrown towards southeast by the Arlui Fault.

Could the Arlui Fault have formed during the Early Jurassic (Pre-Alpine) rifting phase of the Austroalpine passive continental margin, like other normal faults in the Austroalpine Nappes (Froitzheim and Eberli, 1990)? This is unlikely because the Arlui Fault cuts across Alpine structures, in particular, across the large Marbeltal Syncline (Fig. 4) filled with the Raibl Group: In Marbeltal, the hanging wall of the Arlui Fault is formed by Raibl Group of the syncline's core (except for the slivers of Chazforà, Fuorn, and Vallatscha formations directly adjacent to the fault; see Fig. 10), whereas further west (Rauchtal) and further east (between Pedross and Padöll, see Thöni, 1973) the hanging wall is represented by older formations. This means that the Arlui Fault is younger than this syncline which is an Alpine (Trupchun-Phase) structure. It cannot represent a Jurassic rifting fault.

The possibility that the Arlui Fault represents a Cenozoic-age normal fault, comparable to the Engadine Fault (Fig. 2; Schmid and Froitzheim, 1993), can be excluded. This interpretation is inconsistent with zircon (U-Th/He) ages reported by Hölzer et al., which range from ~66 to ~71 Ma in a north-south profile located a short distance east of Karlesspitze. This profile crosses the prolongation of the Arlui Fault. Hölzer et al. (2024) assume a closure temperature of ~170 °C for the zircon (U-Th)H system under the circumstances given in this area. As the dynamic recrystallization of quartz observed in the the mylonites at Karlesspitz requires temperatures of more than 300 °C, the mylonites must have formed before the rocks cooled down to ~170 °C, i.e., before ~70 Ma. The only possible age for the mylonites and for the Arlui Fault is therefore Late Cretaceous (Ducan-Ela Phase).

Hess (1962) and Thöni (1973) interpreted the boundary between the Plawenn Orthogneiss and paragneisses east of Jaggl as the basal thrust of the Ötztal Nappe over the S-charl Nappe. We did not find any evidence for this. Following the ridge from Jaggl towards southeast, we observed the Chazforà Formation resting with a depositional contact on Plawenn Orthogneiss (Fig. 4). Towards southeast, paragneiss follows across a steeply dipping contact, then again orthogneiss, and finally again paragneiss (Fig. 4). If the orthogneiss-paragneiss boundary represented a major thrust fault, the geometry would require tight folding or some other mechanism of duplication of the thrust, for which we also found no evidence.

Figure 12: The Arlui Fault in the Karlestal. **(a)** Vordere Karlesspitze seen from southwest. Coordinates: 46°50′52.3″N, 10°39′55.2″E. Dashed line indicates the Arlui Fault. **(b)** View parallel to the foliation of greenschist-facies mylonite in the Karlestal at 2800 m altitude; dashed line indicates the approximate location of the Arlui Fault. Coordinates: 46°50′59.3″N, 10°41′11.2″E. **(c)** View of a foliation plane; the foliation dips parallel to the hammer handle (dip direction/dip angle: 172/72); the pronounced stretching lineation plunges more to the southeast (plunge direction/plunge angle: 121/61). Diameter of coin is 2.4 cm. **(d)** View parallel to the foliation; shear bands (arrow) indicate top-southeast, normal sense of shear. **(e)** Thin section photograph showing S-C-structure in mylonite from Karlestal, indicating dextral (top-southeast) shear sense. Crossed polarizers. **(f)** Thin-section photograph of relict quartz grain (white) surrounded by fine-grained, dynamically recrystallized quartz. Crossed polarizers.

We therefore assume that the Plawenn body belongs to the Ötztal Nappe. The Ötztal Nappe includes a great variety of orthogneiss bodies (e.g., Klug et al., 2025) and a body like the Plawenn Orthogneiss is nothing unusual.

The mylonitized volcanic rocks along the top of the footwall of the Arlui Fault are probably derived from Permian effusive rocks originally lying on the basement and below the Chazforà Formation. The dykes at the entrance of the Rauchtal may represent feeder dykes of this volcanic complex. The offset of the Arlui Fault, including the part accommodated by shearing in the mylonites, is at least one kilometer (Fig. 4b) but may be larger because

the base of the sedimentary succession is not preserved on the footwall side. The Arlui Fault is a hanging-wall splay of the Schlinig Fault, the major top-east to -southeast low angle normal fault of the area. For the Schlinig Fault, a normal-fault displacement of ~17 km was reconstructed by Froitzheim et al. (1997). The Arlui Fault branches off from the Schlinig Fault near Mals, where the Schlinig Fault makes a bend around a large east-plunging footwall antiform.

The main arguments of Hess (1962) in favour of the window hypothesis are the strong facies similarities, mainly with respect to the Anisian, between the S-charl Nappe and Jaggl and, on the other hand, the facies differences between Jaggl and the Brenner Mesozoic, the sedimentary cover of the eastern part of the Ötztal Nappe ("Wipptaler Fazies" in Hess, 1962). However, Brandner et al. (2003) showed that there is an Anisian facies transition already within the Brenner Mesozoic, from the "typical" Brenner Mesozoic facies in the Southeast to a more "Jaggl-like" facies in the Northwest. Therefore, the Jaggl Mesozoic is not exotic with respect to the cover of the Ötztal Nappe. In general, there is little reason to assume that the facies of pre-orogenic sediments should change at the boundaries of later-formed thrust sheets rather than within these thrusts sheets. Tectonic questions, like the window versus cover setting of the Jaggl Mesozoic, should therefore be investigated primarily by structural methods rather than by facies comparison.

7. Conclusions

- The Permotriassic sedimentary rocks of Jaggl represent a remnant of the sedimentary cover of the Ötztal Nappe. They were first affected by NW-directed thrusting and folding (Trupchun Phase; ~100 to 80 Ma) and then downthrown towards southeast along the Arlui Fault (Ducan-Ela Phase; ~80 to 67 Ma).
- The Arlui Fault comprises a brittle fault plane and, in the footwall, a layer of ductile mylonites derived from Permian volcanic rocks and metamorphic basement.
- All shear-sense indicators in the mylonite give southeast-side-down, normal displacement. We did not find evidence for a thrust shear sense as would be required by the window hypothesis. The "Jaggl Window" does not exist.
- The Arlui Fault is a high-angle hanging-wall splay of the low-angle Schlinig Normal Fault.
- Towards northeast, the Arlui Fault extends into the basement of the Ötztal Nappe as a greenschist-facies mylonite zone at least up to Vordere Karlesspitze and probably beyond.

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