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SEMIDUCTILE DEFORMATION IN PELAGIC LIMESTONES AT DIAGENETIC CONDITIONS

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Abstract: Semiductile to ductile deformation phenomena within unmetamorphic, fine-grained, pelagic limestones of the Northern Calcareous Alps (NCA) in the Eastern Alps were studied. The investigated pelagic limestones include the Triassic Hallstatt Limestone, the Liassic Adnet Limestone, the Middle Jurassic Strubberg Marl and the Upper Jurassic Oberalm Limestone. These pelagic limestones and marls display structures related to semiductile to ductile deformation, including shear planes, solution seams, stylolites and dynamic recrystallization similar to structures in protomylonites due to strata-parallel simple shear. The structures preferentially developed along clay-rich layers and along boundaries between more competent marly limestones showing a protomylonitic appearence due to disjunctive anastomosing foliation. Along the boundaries aragonite and fine-grained calcite were dissolved and insoluble clay minerals were concentrated. Increasing strain resulted in the development of a penetrative foliation, generating S-C fabrics even within competent limestone layers. Furthermore, mesoscale out-of-sequence shear planes caused decomposition of competent limestone layers into clasts and nodules. These clasts acted as rigid objects within a more viscous, argillaceous matrix. When ideally oriented, asymmetric pressure shadows were generated around these nodules and σ-clasts were developed. The transition from massive limestone beds to nodular layers depends on silt and clay contents. While limestones with low clay content were structurally resistant to deformation, clay-rich limestones were easily deformed. The Adnet and Hallstatt limestones formed décollement horizons accomodating high strain during Cretaceous nappe stacking and thrusting within the NCA, while the Strubberg and Oberalm limestones were involved during Tertiary transpressive overprint in large strike-slip faults and thrusting within an associated triangle structure.

Key words: Eastern Alps, pelagic limestone, plasticity, deformation mechanisms, deformation partitioning.

Introduction

Fine-grained pelagic limestones are widespread, among others, within passive continental margin sequences and occur in external fold-thrust belts of many orogens. These commonly comprise variegated micritic limestones of the „ammonitico rosso“-type, widespread in Paleozoic and Mesozoic sequences of the circum-Mediterranean Alpine mountain belts. The typical fabric is domainal including internally undeformed, often fossil-rich lenses and nodules that are surrrounded by stylolitic seams. Compared with recent settings the deposition of these limestones is often assumed to have occurred on deep pelagic swells that were protected from siliciclastic input from the hinterland. Domainal fabrics are usually interpreted to result from sedimentary processes, especially from an interplay between carbonate deposition and dissolution (e.g. Jurgan 1969; Jenkyns 1974; Mullins et al. 1980). A possible tectonic origin for the stylolitic foliation in pelagic limestones was previously described by Tucker (1973) and Alvarez et al. (1978).

Burkhard (1990) demonstrated that even at temperatures between 160–350 °C micritic limestones can plastically deform. Furthermore, various workers (e.g. Schmid 1982; Schmid et al. 1987) showed that calcite is very susceptible to annealing under elevated temperatures (starting with greenschist facies conditions). Experiment-based deformation mechanism maps for calcite predict either pressure solution (Rutter 1976) or creep mechanisms (Schmid 1982) for low temperatures (160–350 °C), small grain sizes (up to 10 μm) and slow strain rates (10^{-13} to 10^{-15} s^{-1}).

We describe and analyse semiductile to brittle deformation within pelagic limestones of the Northern Calcareous Alps (NCA; Eastern Alps; Fig. 1) which have not been affected by any temperature higher than diagenetic conditions (200±50 °C). There, semiductile to ductile fabrics of pelagic limestones, similar to those known from ductile mylonites within metamorphic sequences, reached their final appearence by superimposition of sedimentary and structural processes. We show, furthermore, that these ductilely deformed limestones acted as décollement levels during Alpine nappe stacking. Descriptions of tectonic structures within studied pelagic limestones follow basic work including, e.g. Bell & Etheridge (1973), Dietrich & Song (1984), Hancock (1985), Groshong (1988) and Carrio-Schaffhauser et al. (1990).

The following deformation stages within the central Northern Calcareous Alps produced semiductile deformation phenomena in the pelagic limestones: (1) mid-Cretaceous top-to-the NNE thrusting of the Juvavic nappes; (2) Late Cretaceous syn-Gosau transtension in the entire nappe pile of the NCA; (3) Oligocene NE–SW contraction, and (4) Miocene N–S contraction (Schweigl 1997; Perreson & Decker 1997). Further deformation stages produced only brittle deformation structures, apart from folds.

Geological setting

The Northern Calcareous Alps represent an allochthonous cover nappe complex within the Alpine orogen (e.g. Tollmann 1976; Linzer et al. 1995). They comprise a several kilometres thick, mainly carbonatic passive continental margin sequence of Permian to early Late Cretaceous age. In the central part the NCA are mainly built up by three different tectonic units, from base to top (Fig. 1): (i) the Tirolic Nappe Complex (e.g. Osterhorn Mountains), (ii) the Lower Juvavic Nappe Complex (e.g. the Hallein Unit) and (iii) the Upper Juvavic Nappe Complex (e.g. Berchtesgaden Nappe). Illite-crystallinity data from the Carnian and Permo-Scythian sequences showed diagenetic conditions for the northern and central part of the central NCA (Kralik et al. 1987). The NCA suffered low grade metamorphic overprint (270–320 °C) only along its southern edge (Schramm 1982; Kralik et al. 1987; Gawlick et al. 1994). Apatite fission track ages between 149 and 143 Ma (Hejl & Grundmann 1989) demonstrated that the central Northern Calcareous Alps had already cooled below ca. 100 °C by the end of Jurassic, synchronous with sediment deposition, and have not been heated above this temperature since that time. Spötl et al. (1996) obtained similar ages for the thermal overprint based on ^{40}Ar/^{39}Ar dating of authigenic feldspar and fluid inclusion studies of the same region. Our own apatite fission track data revealed that the temperature was high enough only in the southern sectors of the central NCA to reset apatite tracks (Schweigl 1997). The temperature remained, therefore, below c. 150 °C.

Four different formations with pelagic limestones are intercalated within thick carbonate sequences of the NCA nappe complex (Figs. 1, 2). These are from base to top: (1) the red, nodular, Liassic Adnet Limestone; (2) grey to black Middle Jurassic Strubberg Marl and Limestone; (3) the grey, chert-rich, Upper Jurassic Oberalm Limestone; and (4) red to grey, condensed, Triassic Hallstatt Limestones of the Lower Juvavic Nappe Complex. The first three types of pelagic limestones belong to the Tirolic Nappe of the central NCA. The Hallstatt and Adnet Limestones are quite similar: both have been deposited on deep marine swells, both are condensed fossil-rich limestones (e.g. Tollmann 1976). The Adnet limestones have more clay content and are structurally less competent than the Hallstatt limestones. The Strubberg marls and limestones have been deposited in an oxygen-poor basin and contain siliciclastic material derived from turbidites. They sometimes

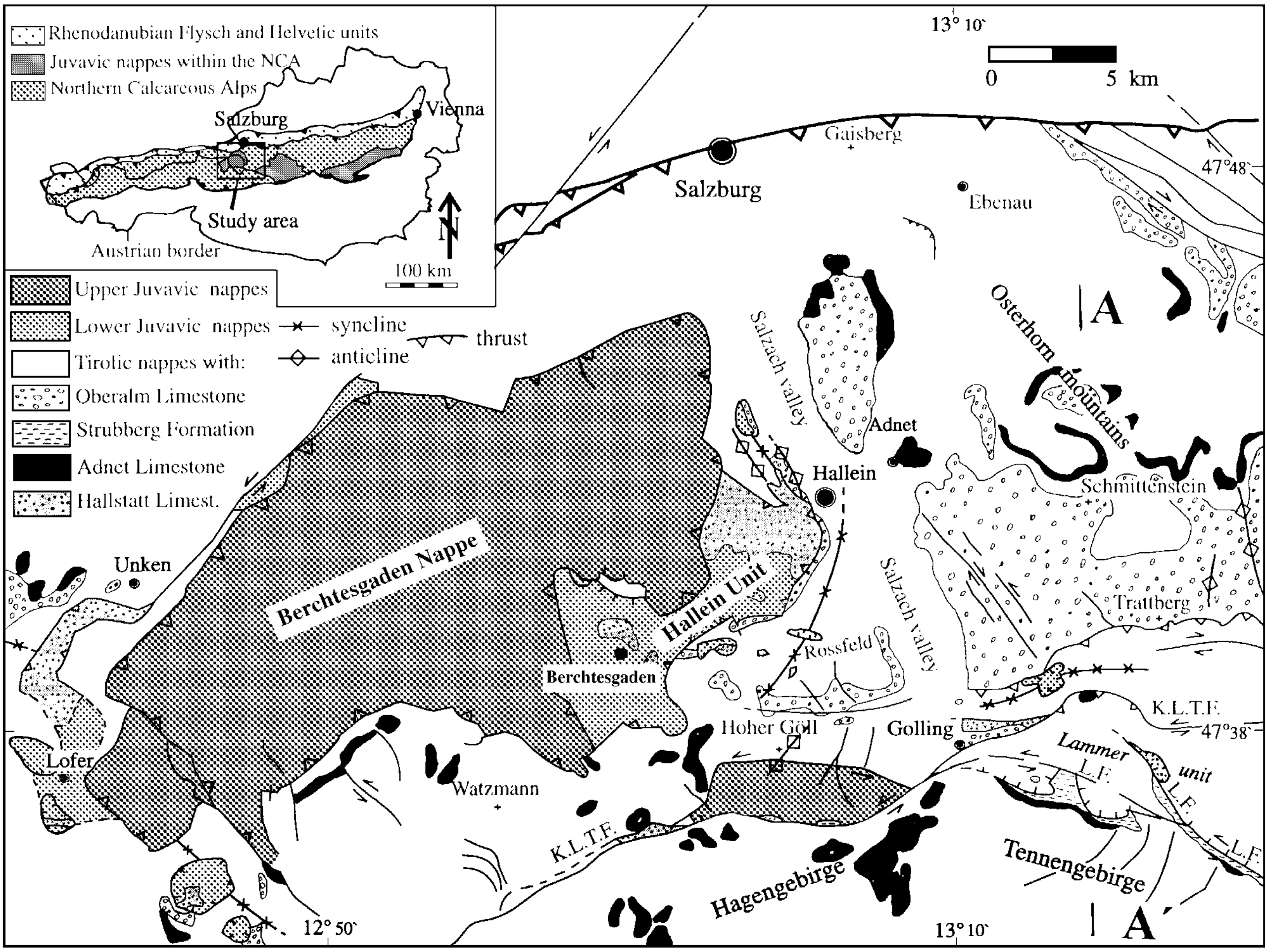


Fig. 1. Structural map of the central Northern Calcareous Alps with distribution of the studied pelagic limestones. A–A′ locates section shown on Fig. 2. L.F.= Lammer Fault, K.L.T.F.= Königsse-Lammertal-Traunsee Fault.

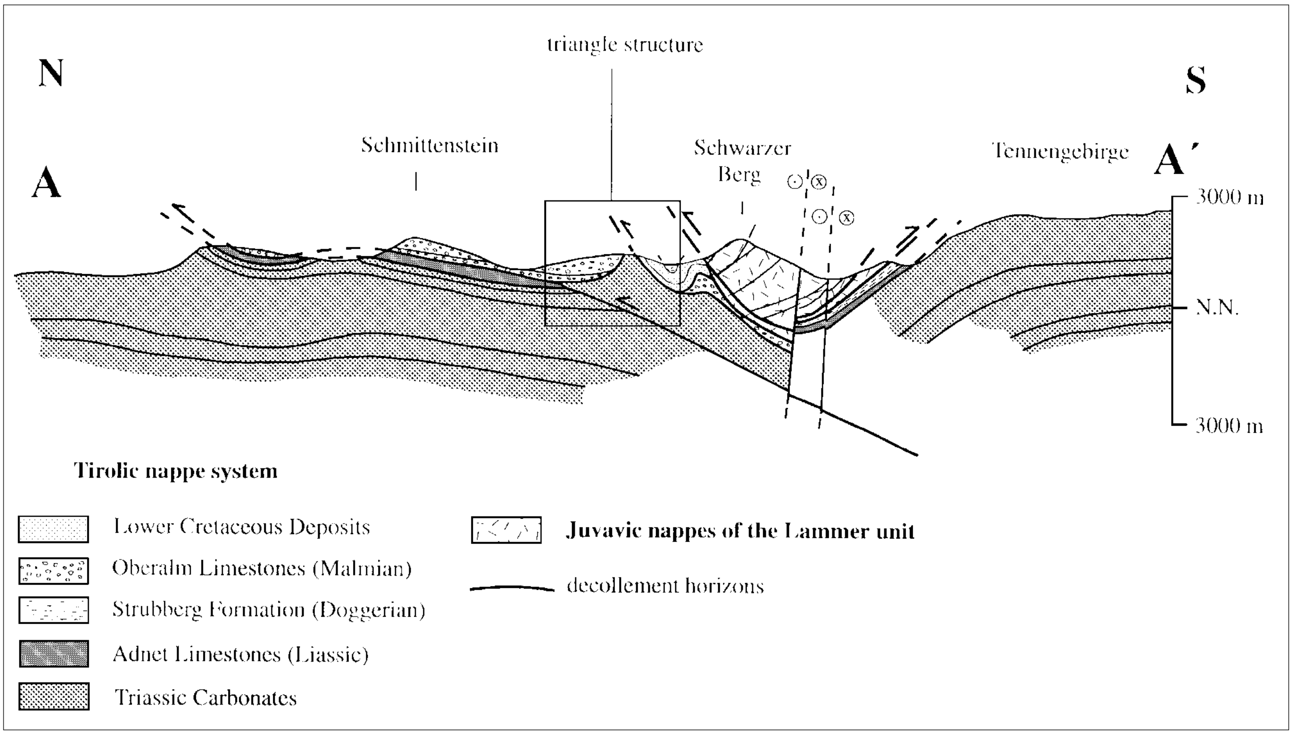


Fig. 2. Cross section with Adnet, Strubberg and Oberalm limestones which were used as décollement horizons. Hallstatt limestones are not exposed in this section. For location of the section, see Fig. 1.

suffered the low grade metamorphism of the southern part of the central NCA. The widespread Oberalm limestones were also deposited in a basin and contain a lot of cherts (Gawlick 1996). They include some metres thick competent limestone layers and marly intercalations.

The pelagic limestones often occur along major décollements along which thrust displacement during Cretaceous and Tertiary nappe stacking occurred, while thick, massive shallow water limestone and dolomite form the competent, stiff interior of those nappes (Fig. 2). The studied samples are from the décollement levels of the Tirolic Osterhorn Mountains and the Lower Juvavic Hallein Unit and from various units along the Lammer and Königssee-Lammertal-Traunsee faults (Fig. 1).

Field observations

The about 40 m thick, Jurassic Adnet Formation is a nodular, phacoidal, relatively thin-bedded, clay-rich, micritic limestone with rich fossil faunas including ammonoidea, well exposed in quarries close to Adnet (Figs. 1, 2, 3). The Adnet Formation itself is divided into several members: The Adnet Limestone sensu strictu represents a micritic red to green, pelagic limestone and the red Adnet Marl comprises a much higher (40 %) clay content than the former (e.g. Tollmann 1976). The Adnet Scheck represents a submarine breccia of Adnet Limestone with clasts within a matrix of white sparite (e.g. Jurgan 1968; Böhm et al. 1995).

Our studies show that stylolitic Adnet Limestone (sensu stricto) forms several strongly deformed structural levels. In all these levels anastomosing stylolitic seams occur subparallel, oblique and perpendicular to the bedding forming a disjunctive anastomosing stylolitic cleavage (according to the nomenclature proposed by Powell 1979). Shear planes, solution seams and stylolites preferentially developed along clay-rich layers and along boundaries of competent limestone beds within the Adnet Limestone (Fig. 4a). Some stylolitic seams are oblique to both bedding and the main stylolitic foliation. In general these portions of the Adnet Limestone have a protomylonitic character, following the definitions given by Wise et al. (1984) and Heitzmann (1985). Along these stylolitic seams aragonite and very fine-grained calcite were dissolved and insoluble clay minerals were concentrated. Increasing deformation resulted in the development of a penetrative foliation generating S-C-fabrics (Berthé et al. 1979) even within competent limestone layers while slip accumulated (Fig. 4a). During advanced stages of deformation mesoscale out-of-sequence shear planes caused decomposition of competent limestone layers into boudin-like clasts and nodules, respectively, that sometimes contain remnants of fossils (e.g. ammonoidea). These clasts acted as rigid particles within a less viscous, argillaceous matrix. When ideally oriented, asymmetric pressure shadows were generated around these nodules until σ-clasts were developed (Fig. 4a). Biogenic and other clasts are flattened and partly dissolved along clast edges. The transition between more or less nodular beds depends on the silt and clay contents. While limestones with very little clay contents are structurally competent, clay-rich limestones may be structurally responsive. Offset of sedimentary dikes (Fig. 4b) with crinoidal infill along cm-scaled, internally

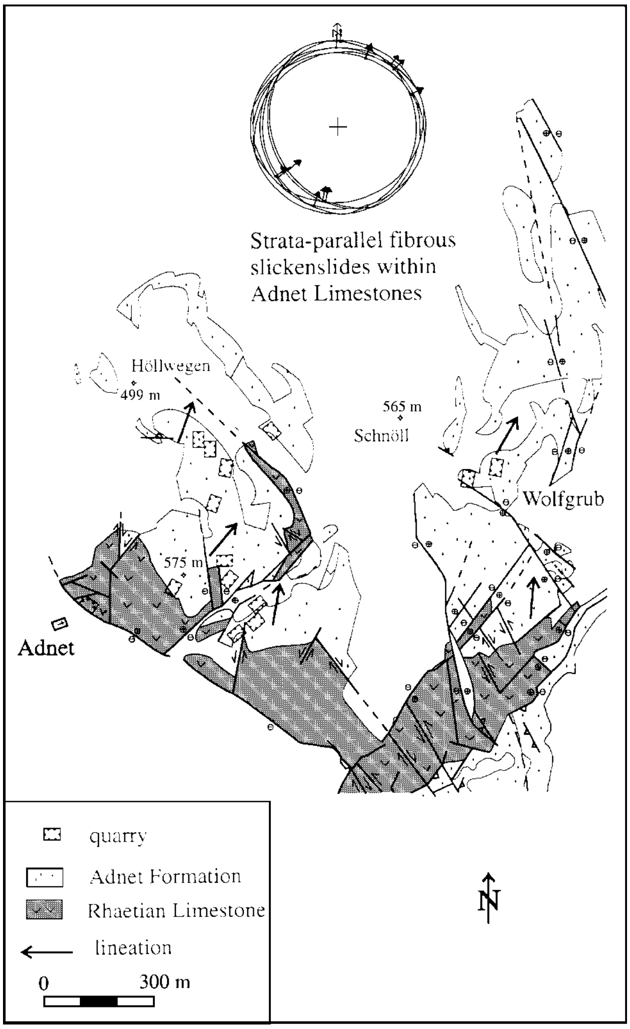


Fig. 3. Structural map of the quarries at Adnet. The stretching lineations of the semiductile deformation structures are parallel to the NNE–SSW oriented, strata-parallel fibrous slickensides.

finely foliated shear zones developed subparallel to bedding planes clearly proves the formation of ductile shear zones in otherwise nearly undeformed limestone. The lineation on the stylolitic cleavage is only weakly developed. It trends NNE to NE (Fig. 3). Strata-parallel slickensides of the Adnet Formation prove top-to-the NNE displacement (Fig. 3).

In the Tauglboden area near the Schmittenstein Mountain we observed steep ductile shear zones in the Adnet Limestones that produced nodular limestones. The contacts between the shear zones and less deformed limestone are very sharp (Fig. 4b). The semiductile shear zones also developed as pinch-and-swell structures where pull-apart structures were filled with calcite (Fig. 4c). Another common feature in these shear zones is the grain size reduction and S-C fabrics. Outside of the semiductile shear zones en-echelon tension gash veins and fibrous slickensides with the same orientation and shear sense occur. This indicates that cataclastic and ductile mechanisms were at work during the same stress and kinematic conditions.

In summary, the nodular, marly members of the Adnet Formation appear semiductilely deformed in all major exposures. A principal feature is the presence of a stylolitic foliation largely subparallel to the sedimentary bedding, and sometimes overprinted by steep shear zones crosscutting bedding and foliation.

The Oberalm Limestone is a fine-grained, grey, pelagic, Upper Jurassic limestone with chert lenses. It reaches a thickness up to 800 meters and the individual beds are decimetres to metres thick. In the Trattberg area the Oberalm Limestone is partly transformed into a coarse grained marble with S-C planes and ecc-planes (ecc: extensional crenulation cleavage: Platt & Vissers 1980; Fig. 4d, e). An anastomosing stylolitic cleavage is spaced on the scale of centimetres. The thick beds are foliated, cm-thick layers of marble and less deformed limestone. The disjunctive cleavage is overprinted by shear bands. These structures document formation of dip-slip faults on the frontal edge of a triangle structure (Fig. 2).

Similarly, the rocks of the pelagic Strubberg Formation often show S-C fabrics and shear bands within semiductile shear zones (Fig. 4f). The grey to black Middle Jurassic Strubberg Formation consists of micritic, radiolaria-bearing limestones, siliceous limestones, marls and marly limestones. These display similar deformational structures as the Adnet Limestone. The Strubberg Formation can reach a thickness of 200 metres and is restricted to the Lammer Valley (Fig. 1). A ductile fabric with S-C fabric and shear planes is common although microfossils are well-preserved within clasts sourrounded by anastomosing foliation.

The Hallstatt Limestone is a colourful, greyish to reddish, Ladinian to Norian limestone with a rich pelagic fauna. The thickness of the thick bedded limestones is about 200 metres (Tollmann 1976). Stylolitic seams, nodular structures and shear bands are present throughout the Hallstatt Limestone in the study area. Ecc- and S-C planes can be observed along fault zones (Fig. 4g) in the Hallein Unit.

Microfabrics

During deformation, twinning and grain size reduction due to recrystallization of originally coarser grained rocks have been the most important mechanisms in all studied samples of all four types of fine-grained pelagic limestones. Thin sections of the Adnet limestones, taken from shear zones, show high degrees of pressure solution, elongation and rotation of grains and biogenic components, e.g. lamellibranchiata shells or crinoidea columnalia (Fig. 5a). Internally less deformed nodules developed by pressure solution and shear band formation (Fig. 5b).

Semiductile shear zones within otherwise undeformed Adnet Limestone show the development of a stylolitic foliation, strong flattening of calcite grains, fossils, and other clasts (Fig. 5b). Clasts and calcite grains show serrated boundaries caused by pressure solution (Fig. 5b). Grain size reduction occurs by two mechanisms: (i) breakage of coarse

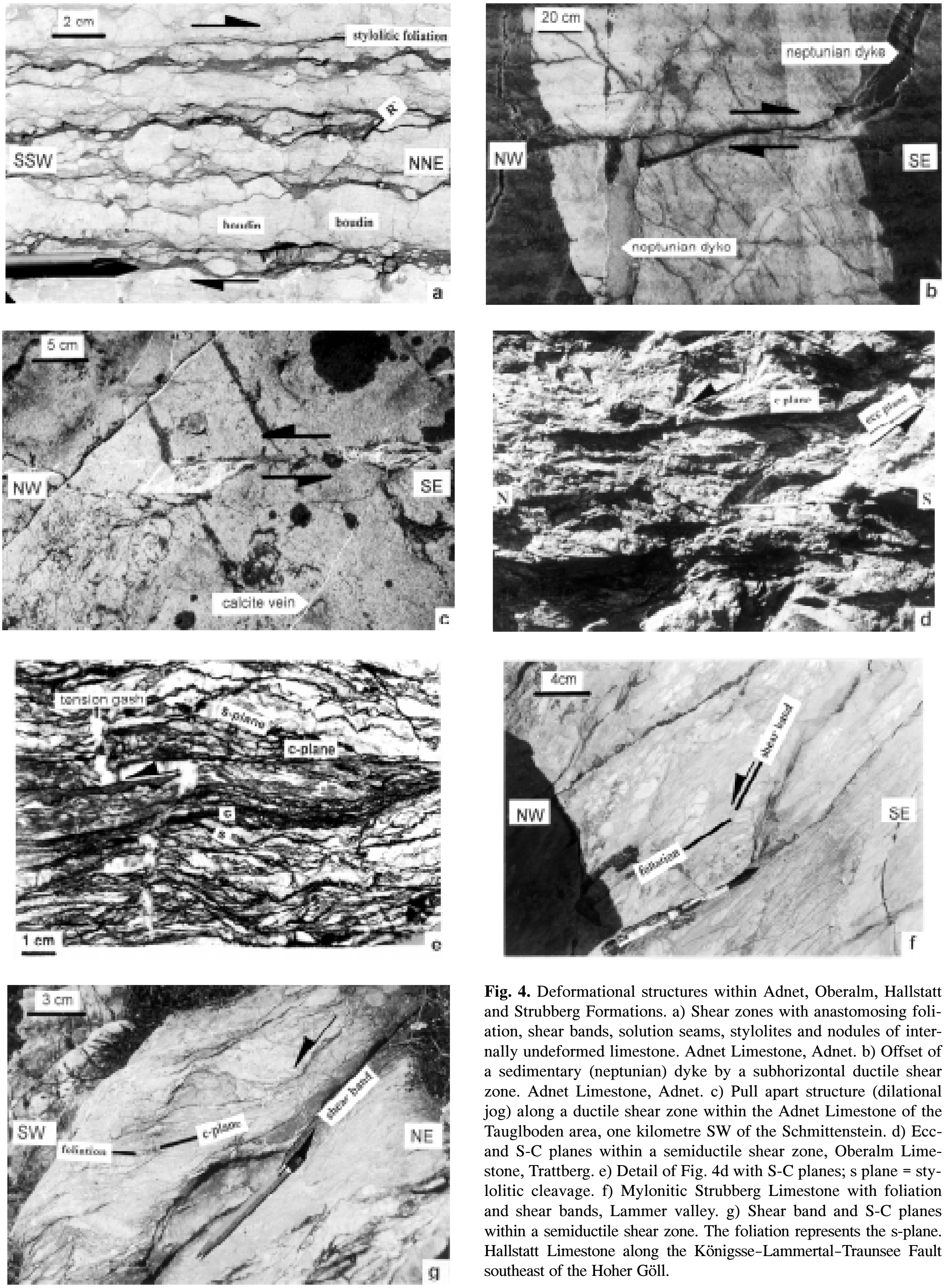
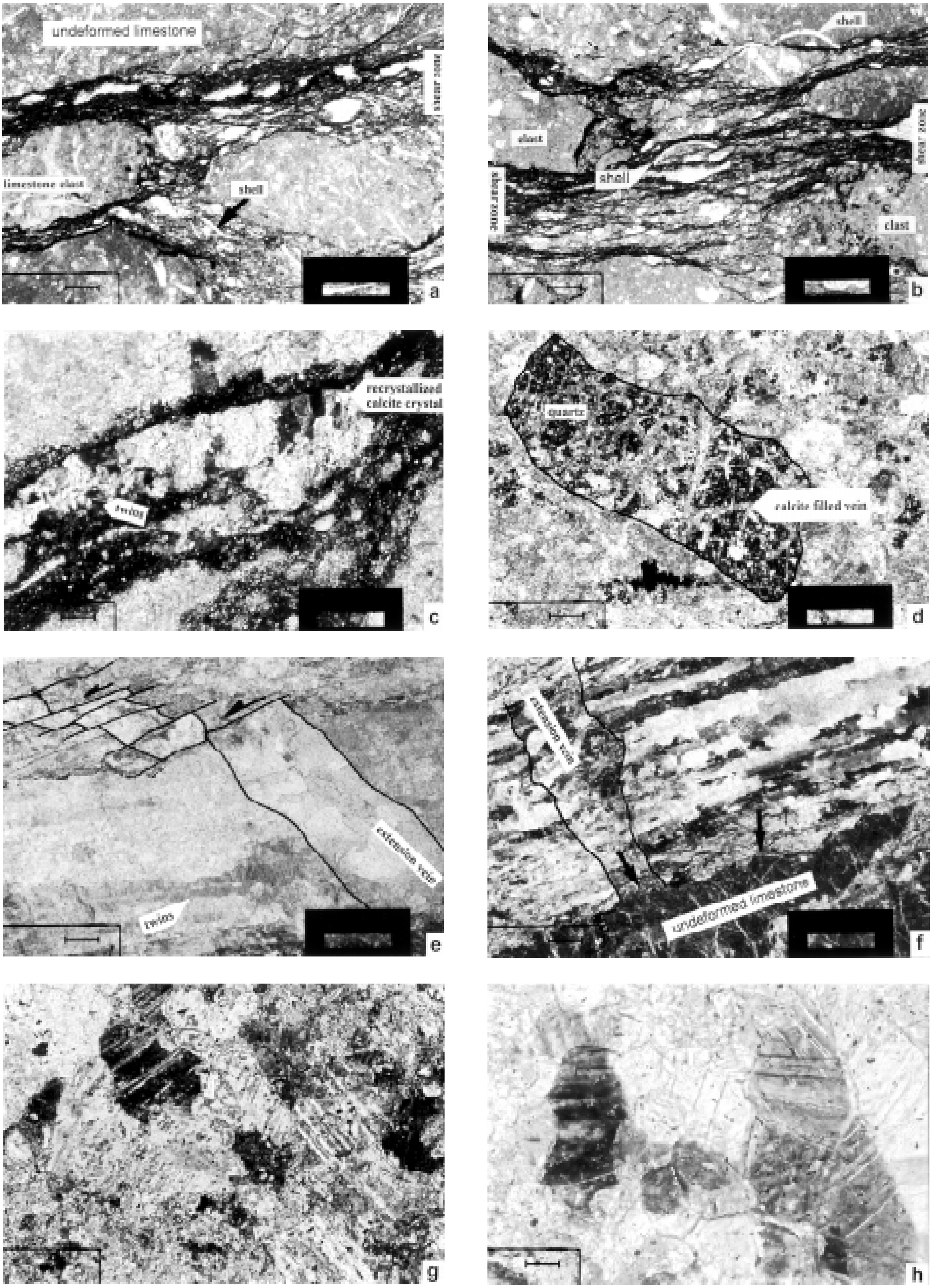


Fig. 4. Deformational structures within Adnet, Oberalm, Hallstatt and Strubberg Formations. a) Shear zones with anastomosing foliation, shear bands, solution seams, stylolites and nodules of internally undeformed limestone. Adnet Limestone, Adnet. b) Offset of a sedimentary (neptunian) dyke by a subhorizontal ductile shear zone. Adnet Limestone, Adnet. c) Pull apart structure (dilational jog) along a ductile shear zone within the Adnet Limestone of the Tauglboden area, one kilometre SW of the Schmittenstein. d) Ecc- and S-C planes within a semiductile shear zone, Oberalm Limestone, Trattberg. e) Detail of Fig. 4d with S-C planes; s plane = stylolitic cleavage. f) Mylonitic Strubberg Limestone with foliation and shear bands, Lammer valley. g) Shear band and S-C planes within a semiductile shear zone. The foliation represents the s-plane. Hallstatt Limestone along the Königsse–Lammertal–Traunsee Fault southeast of the Hoher Göll.


undeformed limestone
shear zone
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a
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recrystallized calcite crystal
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calcite filled vein
d
extension vein
twins
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extension vein
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clasts and calcite grains; and (ii) dynamic recrystallization of coarser calcite grains within narrow zones (Fig. 5c). By this deformation the compact Adnet limestones disintegrate into nodules, resulting in the nodular texture (Fig. 5a, b). The occurrence of nodule-rich and competent layers within the Adnet limestones appears to be solely a result of strain partitioning during strata-parallel simple shear deformation (Fig. 4a).

Shells of lamellibranchiata are oriented parallel to the foliation within shear zones (Fig. 5a, b) and became thinned, disintegrated and elongated at the same time due to ductile deformation. They are also partly dissolved by pressure solution. Calcite grains are often twinned, with up to three twin sets per grain, strongly elongated, and bounded by pressure solution seams. Subgrains are common along edges of calcite grains. Shear bands can often be observed within shear zones, sometimes grading into S-C fabrics.

Shear zones in the Oberalm Limestone show cataclastic to ductile deformation. Quartz grains are broken; resulting gaps are filled with calcite by nucleation recrystallization (Fig. 5d). Relic calcite grains are strongly elongated (Fig. 5e), indicating intracrystalline gliding as one principal deformation mechanism. Within small ductile shear zones calcite grains show decreasing length-width ratios towards the centre of the shear zone (Fig. 5f). Twin lamellae are often bent (Fig. 5e). Shear zone boundaries to undeformed country rocks are very sharp (Fig. 5e, f). The contact zone between ductile shear zones and country rocks shows cataclastic deformation and pressure solution (Fig. 5f). S-C fabrics developed in the interiors of the shear zones. Dynamically recrystallized calcite grains bear serrated and lobate grain boundaries (Fig. 5g) and parallel oriented grain shapes (Fig. 5f). Grain boundary migration, subgrain formation and undulose extinction together with twinning indicate further important deformation mechanisms (Fig. 5g). Dynamic recrystallization of calcite (Fig. 5h) and cataclasis are responsible for grain size reduction.

Narrow (centimetre to metre thick), semiductile shear zones with shear bands, foliations and stylolites occur in the Hallstatt Limestone of the Hallein Unit and along the Königssee–Lammertal–Traunsee fault (Fig. 1), too. In areas between shear bands strongly elongated calcite grains were dynamically recrystallized. Insoluble clay minerals are concentrated along pressure solution seams.

Displacements of calcite veins along shear zones, elongation of calcite grains, shear bands and stylolitic foliation can be found in marls and limestones of the Strubberg Formation. Grain boundaries of calcite are serrated due to pressure solution. Quartz grains show undulose extinction, partly serrated to lobate grain boundaries and the formation of subgrains. But the temperature reached was obviously too low to permit dynamic recrystallization of quartz. On the other hand calcite displays widespread dynamic recrystallization. Mylonitic Strubberg marls and limestones with extreme grain size reduction, elongation of calcite grains, shear band formation, folding, and the associated development of a axial plane foliation occur within a 10–100 m wide shear zone in the Lammer Valley (Fig. 6a). Depending on the primary layering of differing grain sizes and mineral composition, fine-grained and clay-rich layers preferentially formed ductile mylonites, while coarse-grained, calcite-dominated lithologies display cataclastic fabrics (Fig. 6b). S-C fabrics, shear bands and stylolites developed in cataclastically and ductilely deformed layers (Fig. 6b, c). Partly because the amount of finite strain was so high, only quartz grains survived as clasts in the mylonitic calcitic matrix (Fig. 6c). Clastic quartz grains are undulose, sometimes corroded or broken. Relictic calcite grains are strongly elongated and their twin lamellae are bent. Cataclastically deformed calcite grains, cut by shear bands, are surrounded by a mylonitic calcitic matrix (Fig. 6b). Calcite grains can display undulose extinction.

Shear strain determination

Two methods of shear strain determination on the Adnet limestones in the quarries of Adnet (Fig. 2) were used: a) an absolute shear strain determination using the offset of a sedimentary dyke along a ductile shear zone (Fig. 4b) according to a method described by Ramsay (1980) and Ramsay & Huber (1983); and b) the analysis of two-dimensional strain from the preferred orientation of lines, derived from bivalvia shells, described by Panozzo (1984).

Absolute shear strain γ within the ductile shear zone that offsets the neptunian dyke in the Adnet Formation was calculated by the ratio between the offset distance and the thickness of the shear zone. The strain measurement was used for high strain Adnet Limestone. Absolute shear strain was calculated:

$$\gamma = \tan\Psi = \text{offset/thickness (of the shear zone).}$$

←

Fig. 5. Microfabrics of the Adnet and Oberalm Limestones. a) Formation of nodules by pressure solution and shearing within semiductile shear zones. The nodules are internally undeformed. Note aligment and sigmoidal shape of filaments (shells) within shear zones. Adnet Limestone. Scale bar: 40 μm. b) Shear bands and pressure solution seams play an important role within shear zones. Parallel orientation of shells and flattening of biogenic clasts within shear zones. Adnet Limestone. Scale bar: 40 μm. c) Dynamic recrystallization of calcite within small shear zones. Adnet Limestone. Scale bar: 5 μm. Note that new grains are twinned. d) Broken quartz grain. Nucleation recrystallization of calcite within the veins of the quartz grain. Cataclastic Oberalm Limestone; scale bar: 40 μm. e) Ductile shear zone with twinned calcite grains and recrystallized grains is cut by a calcite vein, which is offset by a stylolitic cleavage. Oberalm Limestone. Scale bar: 10 μm. f) Ductile shear zone with dynamic recrystallization by subgrain rotation. Old calcite grains are strongly flattened and parallel-oriented. At the boundary between the shear zone and the undeformed pelagic limestone cataclasis (arrows) occurs. The ductile shear zone is cut by a calcite vein. Oberalm Limestone. Scale bar: 40 μm. g) Calcite grains showing grain boundary migration, subgrain formation, twinning and undulose extinction. Oberalm Limestone. Scale bar: 10 μm. h) Dynamic recrystallization of calcite. Old grains are twinned and new grains show a polygonal grain shape. Oberalm Limestone. Scale bar: 5 μm.

The average absolute shear strain γ resulted in a value of ca. 42. Minimum and maximum value, depending on the change of the thickness of the shear zone along strike range between 22 and 268.

The Panozzo method (Panozzo 1984) is based on distribution of originally randomly distributed lines in a rock volume. Therefore, we made thin sections parallel to foliation of ten Adnet Limestone samples containing shear zones from one quarry of Adnet (Salzburg). The thicknesses of the shear zones range between some millimetres and one centimetre. Then we digitized the bivalvia shells within and outside the semiductile shear zones with the help of the Panozzo program created by R. Ott (see Ratschbacher et al. 1994). The shear strain was calculated by:

$\gamma = a / b$ (long and short axis of strain ellipse).

Average shear strain measured by the orientation of shells from twelve analysed shear zones of the thin sections resulted in a value of 4. The shear strain value ranged between 2 and 10. Average shear strain of the irregularly oriented shells outside the shear zone within nearly undeformed Adnet limestones resulted in a shear strain value of 1.4.

The shear strain values of the Panozzo method are much lower than the values of ductile shear zones which offset the neptunian dykes because within the semiductile shear zones strain is partially stored in twinning, in shear bands and by pressure solution that is not measured by the Panozzo method. The shear strain determined by the Panozzo method yields an average strain value for the semiductilely deformed limestone. The strain analysis support the idea of strain partitioning and presence of high strain zones within the Adnet Limestone.

Discussion

From the above presented structural data it appears that all four studied pelagic limestone formations partly include a domainal protomylonitic fabric. In ductile shear zones the Hallstatt, Adnet, Strubberg and Oberalm limestones show a clearly developed planar fabric and parallel arrangement of minerals and biogenic components, e.g. shells.

In shear zones the pelagic limestones show clear indications of both ductile and cataclastic deformation. Cataclasis is characterized by fracturing of the minerals like calcite and quartz and by frictional slip within the Hallstatt, Strubberg and Oberalm limestones. The grain size reduction is achieved by cracking and fracturing of minerals and components, e.g. fossils. Fracturing in calcite and quartz grains ceased with grain size reduction. Minerals and biogenic components mostly lack preferred orientation.

The minerals and fossils are strongly elongated and corroded by pressure solution. Pressure solution played an important role during ductile deformation processes in pelagic limestones, especially at the formation of nodular limestones. There is ample evidence in naturally deformed rocks that pressure solution is a common deformation mechanism at relatively low temperatures (e.g. Alvarez et al. 1978; Schmid 1982). The amount of pressure solution was not determinable because solution and redeposition are mostly very distant in space.

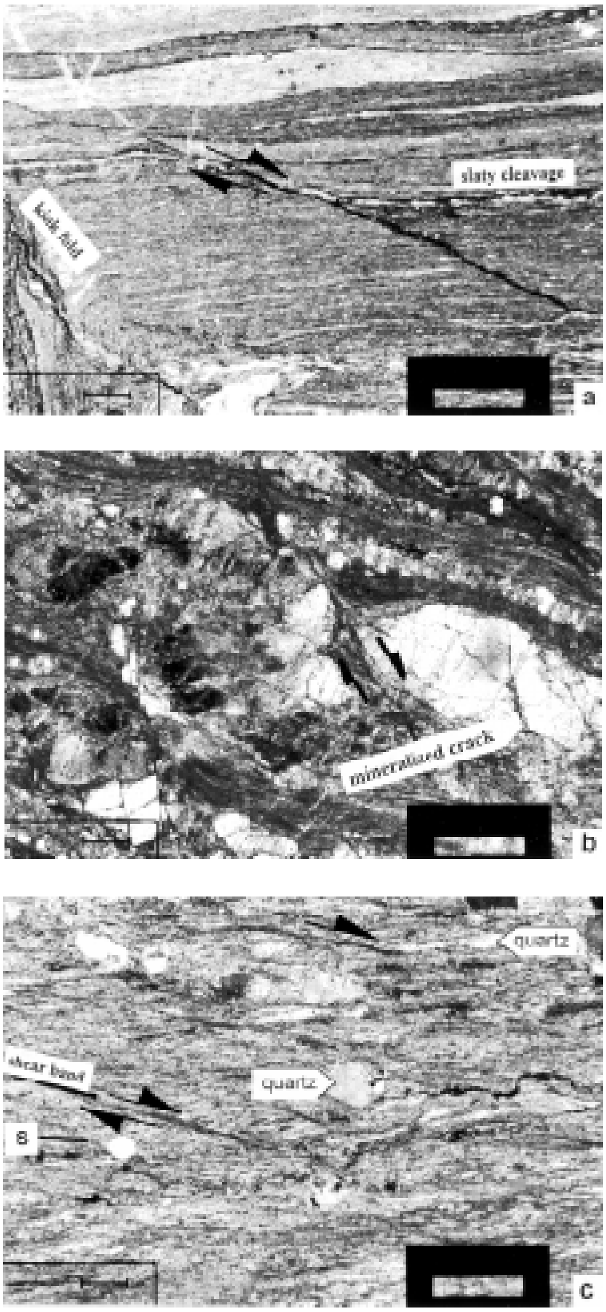

Fig. 6. Microfabrics in marls and limestones of the Strubberg Formation. a) Strubberg Marl with slaty cleavage, with a kink fold and second axial plane foliation that is a disjunctive cleavage. Mylonitic Strubberg Marl; scale bar: 40 µm. b) Brittle to ductile deformation in a shear zone. Calcite grains are broken, undulose, cut by shear bands and show cataclastic fissures. Ductilely deformed layers consist of fine-grained calcite and clay minerals. Protolith was a turbiditic sequence within the Strubberg Marl. Scale bar: 10 µm. c) Shear bands and foliation (s) appearing as a zonal crenulation cleavage. Quartz clasts are flattened, corroded and sometimes rotated. Initial stage for σ- or δ-clast formation with recrystallization tails is achieved. Strubberg Marl; scale bar: 10 µm.

Oblique stylolites, asymmetric pressure shadows of σ-clasts, shear bands and S-C fabrics were used as kinematic indicators. Those prove a dominant strata-parallel simple shear deformation with top-to-the NNE displacement of hanging wall units during semiductile deformation (Schweigl & Neubauer 1997).

The calcite recrystallized dynamically; the quartz shows undulose extinction and subgrains developed. The grain size reduction was achieved by dynamic recrystallization. Two types of dynamic recrystallisation can occur within these ductile shear zones: the more common one is dynamic recrystallization by subgrain rotation, called rotation recrystallization (Guillope & Poirier 1979), mainly concentrated in grain boundary regions (Fig. 5h). The second one is nucleation recrystallization (Guillope & Poirier 1979), caused by a nucleation and growth mechanism and concentrated in relatively undeformed domains liked calcite veins (Fig. 5g). This mechanism produced smaller grains than rotation recrystallization.

A study by Olsson (1974) on various calcite rocks of different grain sizes showed that in the temperature range of 25–300 °C yield stresses increase with decreasing grain size. Not only are stress intensity and temperature responsible for the kind of deformation seen in pelagic limestones, but also the clay content, fluid content and grain size of the pelagic limestones. In experiments on calcite rocks Schmid (1982) and Schmid et al. (1987) demonstrated that in addition to the strain rate, temperature and differential stress, the grain size is a parameter of significant importance for the flow law conditions. The work hardening effect of a small grain size is due the fact that grain boundaries are obstacles to free propagation of slip and twinning (Schmid 1982). At high stresses a larger grain size leads to lower strength. The dominance of strata-parallel semiductile shear zones within fine-grained limestones, intercalated within coarse-grained shallow water limestone and dolomite, leads to the conclusion that the fine grain size represents the governing factor of shear zone formation.

Also the primary thickness of individual layers has an important influence whether ductile or brittle deformation dominates. Due to strain partitioning different deformation mechanisms occurred under the same stress conditions in the same lithology.

A change from pressure solution mechanism into diffusional creep or towards intracrystalline plasticity for fine-grained calcite rocks is only achieved by differential stresses in excess of 100 MPa (Schmid 1982). This implies that the pelagic limestones could have suffered such stresses.

All considered, pelagic limestones form major décollement levels and flats along which thrust displacement during Cretaceous to Tertiary nappe stacking and transpression occurred (Schweigl 1997), while massive shallow water limestones and dolomites form the competent stiff interior of nappes (Fig. 3). There are also other pelagic limestones of the central NCA forming subordinate décollement levels, e.g. the Early Cretaceous Schrambach marls.

Micritic pelagic limestones can suffer semiductile deformation with protomylonitic fabrics under diagenetic to low grade metamorphic conditions. Important deformation mechanisms like pressure solution, dynamic recrystallization of calcite, twinning and grain boundary sliding of calcite within pelagic limestones can also operate at these low temperature conditions: old calcite grains of about 50 μm grain size recrystallize in grains of some μm. Creep by grain boundary sliding leads to a superplastic behaviour (see also Schmid et al. 1987), that implies extreme ductility in the extension of materials. Quartz in such an environment only shows undulose extinction, some minor elongation of grains and development of subgrains. The primary bedding, the grain size and the clay contents of the pelagic limestones are responsible for strain concentration and resulting ductile or cataclastic deformation. In the same shear zone, cataclastic and ductile deformation can occur simultaneously depending on grain size and original mineral composition of the individual layer. At extreme mylonitization only quartz survives and is sometimes rotated, but real porphyroclasts, as defined by Passchier & Simpson (1986), with recrystallization of porphyroclastic material within pressure shadows, were not found. The contacts between shear zones and surrounding, undeformed limestones are always very sharp.

In summary the following deformation mechanisms acted under low temperature conditions within the shear zones of the pelagic limestones: i) cataclastic flow, ii) intracrystalline deformation like dislocation glide and twinning, iii) glide and climb (power law creep) and iv) pressure solution. A final conclusion is that ramp-flat geometries of imbricated passive continental margin sequences that mostly contain carbonates are largely controlled by the presence of pelagic limestones.

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