Published in Terra Nova 12 : 281-288, 2000,
which should be used for any reference to this work

Brittle–ductile deformation in the Glarus thrust Lochseiten (LK) calc-mylonite

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ABSTRACT

The Glarus thrust accommodated at least 30 km of northward displacement strongly localized within a 1-m layer of 'Lochseiten' (LK) calc-mylonite. This layer displays veins in various states of plastic deformation and a wildly refolded foliated gouge texture. Lattice- and shape-preferred orientations are observed within the fine-grained, recrystallized matrix. These features indicate the alternate activity of brittle and ductile deformation mechanisms. In contrast to the classical view that grain boundary sliding (superplasticity) is the dominant deformation mechanism, it is advocated that fluids, derived from the footwall and expelled along the thrust, are responsible for hydrofracturing and cataclastic deformation. In periods between fracture events, deformation was ductile. In this new interpretation, a substantial amount of the total thrust displacement was accommodated by numerous short-lived and strongly localized fracture events at the base of the Verrucano thrust sheet, rather than a permanently weak décollement lithology.

Introduction

Large overthrusts have been recognized since the end of the 19th century, but a mechanical paradox quickly appeared because the motion of large rock masses along low-angle thrust faults seemed mechanically impossible, or restricted to distances smaller than about 10 km (e.g. Hsü, 1969). Proposals to solve this problem include: (i) large strength contrasts between exceedingly weak rocks in the décollement horizon and much stronger ones within the thrust sheet; (ii) propagation of incremental slip domains; and (iii) close to lithostatic fluid pressures within the décollement horizon (e.g. Schmid, 1975; Price, 1988; Henry and Le Pichon, 1991; Twiss and Moores, 1992).

Displacement along the Glarus thrust is at least 30 km (Pfiffner, 1985) (see Fig. 2). This thrust is a very well defined fault underlined by a thin layer of the famous 'Lochseitenkalk' (LK) (Heim, 1921). Classically, the LK is interpreted to be smeared out Mesozoic carbonates from footwall and/or hanging wall (Schmid, 1975; Pfiffner, 1982). Superplastic flow has been proposed as the dominant deformation mechanism within the LK to explain the extremely high strains 'without necking' (Fig. 1) and as a solution to the mechanical paradox of large overthrusts (Schmid *et al.*, 1981; Schmid, 1982a). Earlier speculations about the mechanics of the Glarus thrust involved lithostatic fluid pressures (Hsü, 1969). Based on strongly altered stable isotope signatures within the LK and structural observations, Burkhard and Kerrich (1990) and Burkhard *et al.* (1992) proposed a veiny origin for most, if not all of the mylonite calcite.

This contribution presents new structural and microstructural observations relevant to the discussion of the origin and structural evolution of the LK and the mechanics of this large overthrust.

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Geological setting

Tectonic units at the front of the Alps in Eastern Switzerland (Fig. 2) are subdivided into a 'Helvetic complex' above and an 'Infra-Helvetic complex' below the Glarus thrust (Pfiffner, 1981; Pfiffner, 1993). The Helvetic Glarus nappe comprises Permian Verrucano overlain by a concordant Mesozoic series. The 'Infrahelvetic' complex consists of a crystalline basement overlain by a sedimentary cover of Mesozoic carbonates and Tertiary Flysch and some South Helvetic and Penninic (Sardona) Flysch. The latter were emplaced onto the parautochthonous carbonates in early Oligocene times during the 'Pizol phase' (Pfiffner, 1977). In a second, main deformation stage (Calanda phase), the whole Infrahelvetic complex was intensely folded and imbricated. Thrusting of the Glarus nappe (Ruchi phase) postdates these deformations (Pfiffner, 1977) in an out-of-sequence manner.

Metamorphism ranges from anchizone in the North to lower greenschist facies in the South (Frey, 1988; Rahn *et al.*, 1995). The peak of this metamorphism postdates the Calanda phase deformations (Groshong *et al.*, 1984) estimated at 30–25 Ma. The 'anchi-/epizone-boundary' is offset along the Glarus thrust by about 2 km (Groshong *et al.*, 1984, Fig. 3; Frey, 1988) as the result of postpeak-metamorphic thrusting between 25 and 20 Ma (Hunziker *et al.*, 1986).

Macroscopic observations at the Glarus thrust contact

The Glarus thrust is characterized by the presence of a continuous thin layer (20 cm to 5 m) of calc-mylonite (LK) and a strongly asymmetrical strain gradient away from the contact. Thrust-related deformations are virtually absent 2–5 m below the contact, whereas strong mylonitic foliations, subparallel to the main thrust, can be observed tens of metres above it and fading out gradually into the hanging wall. In this paper, attention is focused on structures within the LK; for a complete description of the structures in the footwall and hanging wall (Fig. 3) see Schmid (1975), Siddans (1979), Burkhard *et al.* (1992) and Lihou (1996). Schmid

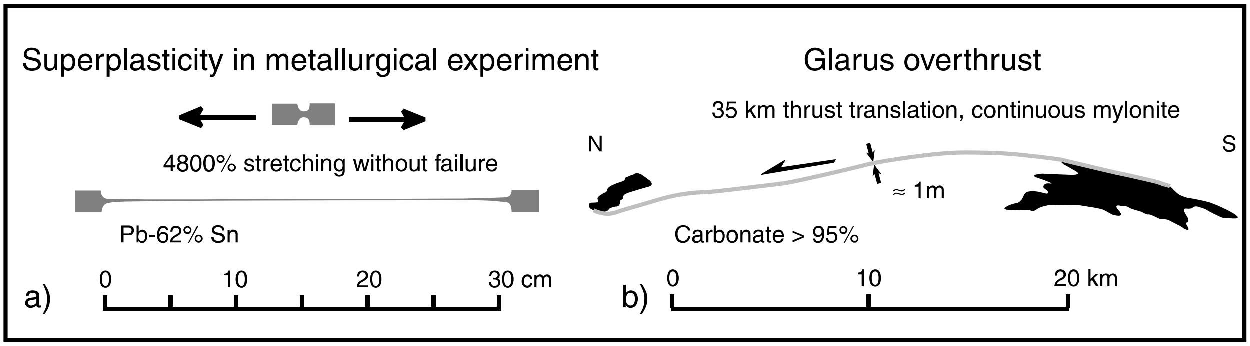


Fig. 1 Superplasticity has been proposed as an explanation for the extreme strain localization in the Lochseiten calc-mylonite (Schmid *et al*., 1977). (a) Superplastically deformed Pb–62%Sn alloy in a metallurgical stretching experiment from Langdon (1982). (b) Schematic cross-section of the Glarus thrust. A metre-thick calc-mylonite connects Mesozoic carbonates in the footwall and hanging wall over a total thrusting distance of about 30 km N–S; drawn to scale, the calc-mylonite would measure less than 2 μm thick in this figure.

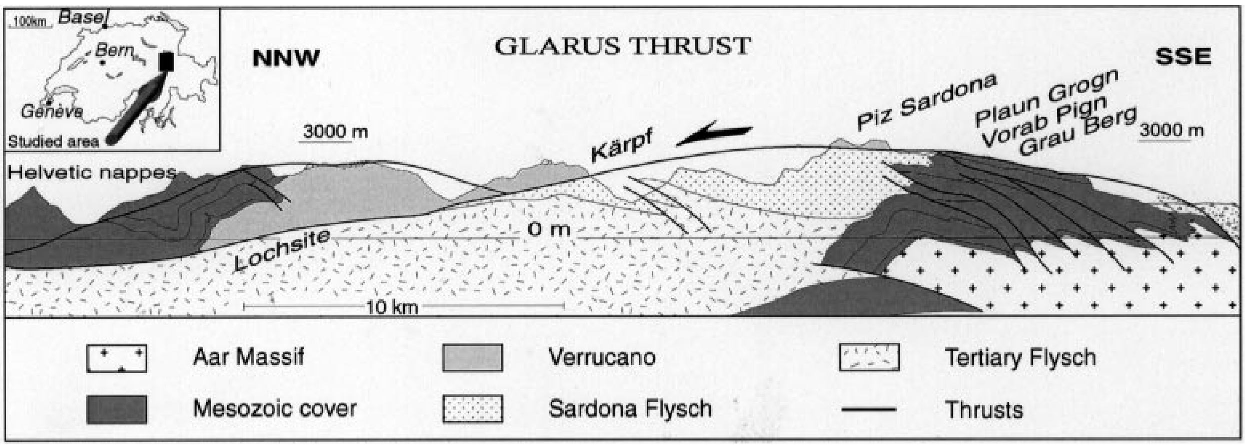


Fig. 2 Tectonic overview of the central, accessible portion of the Glarus overthrust (modified from Oberholzer, 1933). Some of the key localities mentioned in the text are indicated for their relative position in a NNW–SSE profile. North of the type locality 'Lochsite' the thrust surface plunges below topography; it re-emerges some 15 km further north.

(1975) and Burkhard *et al*. (1992) described the turbulent appearance of the LK owing to the refolded alternation of white, pure calcite and black stylolitic layers. This banding locally defines sheath folds and very complex 3D patterns (see Fig. 5A, left-hand side). Neither pervasive schistosity nor stretching lineation are observed within the classic LK (Schmid, 1975). The so-called 'septum' is a conspicuous extremely thin (mm to cm) planar horizon crosscutting all internal structures of the LK. It consists either of gouge or a very sharp shear zone and has been interpreted to have resulted from some modest, late motion of the Glarus nappe (Schmid, 1975).

The lower contact of the LK with the flysch is strongly cuspate-lobate (Schmid, 1975) (Fig. 3). The upper contact with the Verrucano, as well as lower contacts with Mesozoic carbonates (in the South) are irregular too, but lobes and cusps have smaller amplitudes. The pattern of cusps and lobes seems to indicate a higher viscosity for the LK than for the flysch or Verrucano. This observation, confirmed by the boudinage of LK in the flysch, contrasts with the expected weak behaviour of the calc-mylonite (see Schmid, 1975).

In the south, where the footwall consists of Mesozoic carbonates, LK seems to be derived from the former and has a generally smoother appearance (Fig. 5B) with a locally pervasive foliation and well-developed stretching lineation (see also Pfiffner, 1982).

In a few places, lenses of Verrucano are trapped within the LK. They can be interpreted either as slivers of tectonically emplaced Verrucano within the LK, or as 'islands' of Verrucano isolated from their surrounding country rock by the addition of massive calcite veins, affected by strong ductile overprinting and folding near the basal thrust contact. West of Risetenpass, the LK deviates significantly from its ordinary planar configuration, describing a N-vergent fold of metric amplitude with flysch in the anticline core. This fold demonstrates clearly that ductile deformation con-

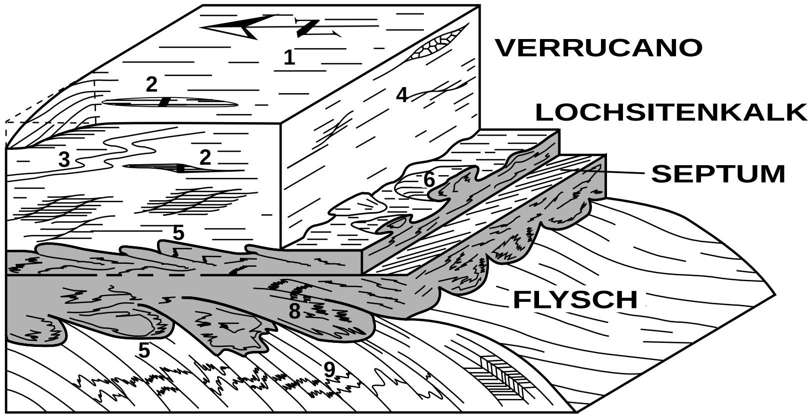


Fig. 3 Schematic overview of macroscopically observed structures within the LK and its contacts with flysch in the footwall and Verrucano in the hanging wall (modified after Burkhard *et al.*, 1992). In the flysch, a steeply dipping foliation (Calanda phase) can be transposed totally by a younger crenulation cleavage (9) within the last few metres below the contact (Ruchi phase). In the Verrucano a well-developed foliation, subparallel to the thrust, is increasingly mylonitic towards the contact. Stretching lineations in the hanging wall (1) have a very constant N–S direction (compare Siddans, 1979). Crenulations (3) within the Verrucano immediately above the contact have N–S-orientated fold axes, parallel to the stretching lineation. Further up, however, crenulations are orientated E–W. Abundant C′ shear bands (4) and asymmetric strain fringes (2) on pyrite grains consistently indicate thrusting towards the North. Structures in the LK (see also text) include: 5, cuspate/lobate contacts; 6, sheath folds; 7, 'septum'; 8, internal banding: strongly folded, sheared and crumpled stylolites and former veins.

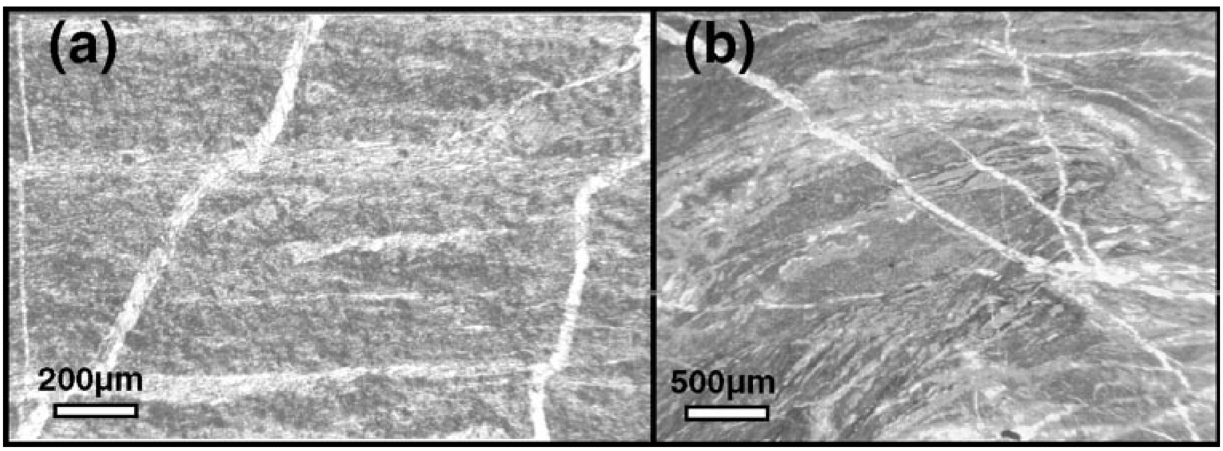


Fig. 4 Photomicrographs of Lochseiten calc-mylonites: (a) sample from Grau Berg (736.300/192.900), south; (b) foliated gouge structure in a sample from Lochsite (725.860/206.400), north.

tinued after the formation of some planar LK (see also Schmid, 1975). In some places, the LK–Verrucano contact exhibits macroscopic evidence of brecciation and cataclasis (e.g. at Ringelspitz and Pizol) (Fig. 5A, right-hand side).

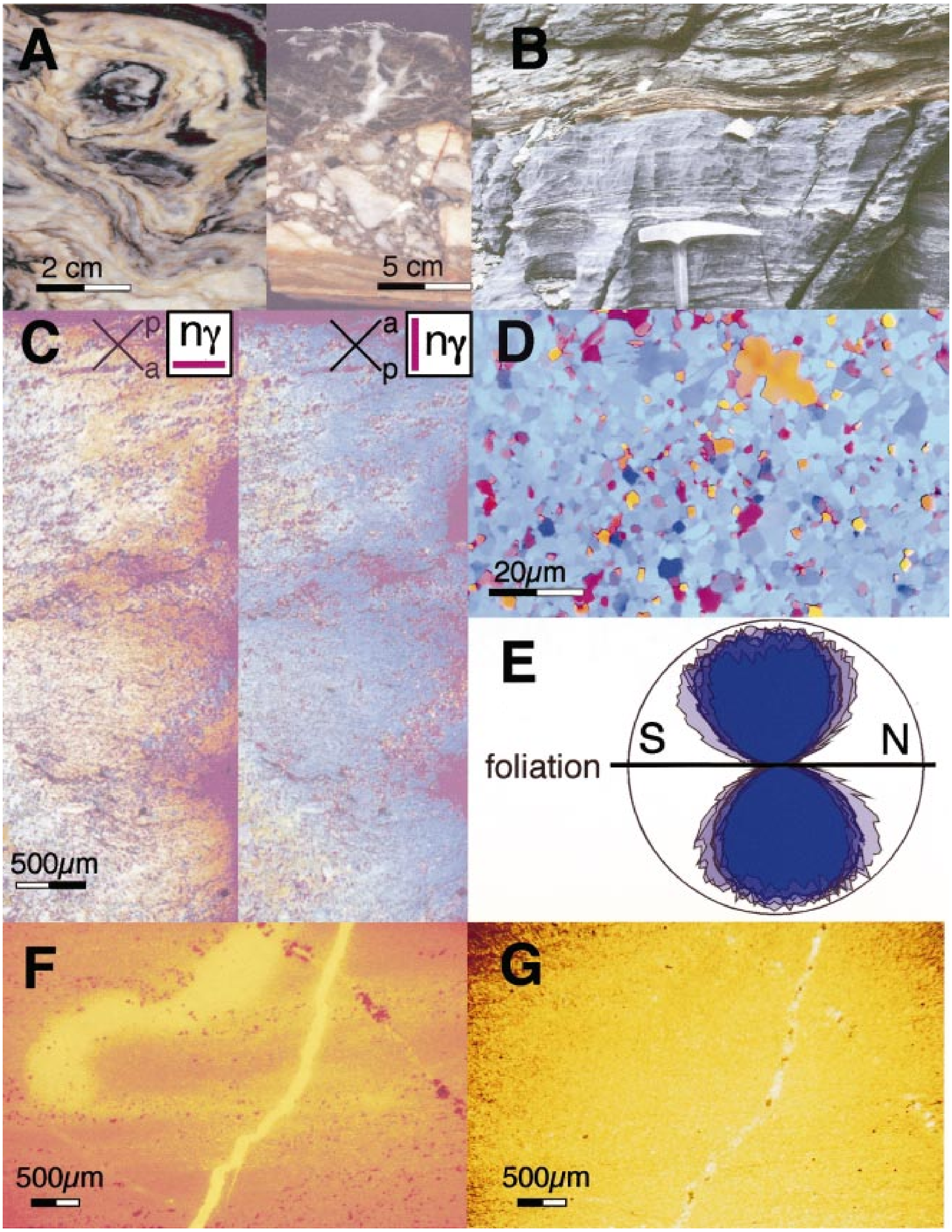
Microscopic observations

Thin-section observations

At low magnification, typical LK from the northern areas exhibits the chaotic structure of a foliated and folded cataclasite (cf. Snoke *et al.*, 1998, Fig. 16; and our Fig. 4b). The foliation is underlined by the alternation of dark stylolitic and light coloured layers. The light layers can often be identified as former veins variably fractured, folded and sheared (see also Burkhard *et al.*, 1992). Several generations of veins can be distinguished. In the southern areas, the structure is smoother and locally a true planar foliation is developed (Fig. 4a). However, former white veins parallel to this foliation can still be recognized. In both types of LK, younger veins crosscut the general structure at high angles, even these latest veins are often fractured and sheared (Fig. 4a).

Optical microscopy on ultra thin sections

Microstructures on the grain scale within the LK mylonite are observed in ultra thin sections (< 3 μm) where calcite appears in different shades of grey. Grain size ranges from > 100 μm to < 1 μm. Coarse grains clearly belong to veins and are always heavily twinned (type III or IV according to Burkhard, 1993) (Fig. 6a,b). Intermediate size grains occur in



isolation within a matrix of very fine grains (< 5 μm). Vein calcite grains display variable degrees of disruption and exhibit ample evidence for dynamic recrystallization (Fig. 6a,b) in the form of subgrains, sutured grain boundaries and a mortar structure. Grain boundary migration (GBM) is observed clearly on thick twins (type IV according to Burkhard, 1993). Increasing deformation and associated recrystallization causes coarse and intermediate grains to be progressively replaced by very small 'matrix' grains. In contrast to the strongly sutured grain boundaries of large and intermediate grains, very fine grains have more regular, smoother grain boundaries, but bulging still documents GBM (Fig. 6c,d). Even very small grains of less than 2 μm are occasionally twinned, as already pointed out by Schmid *et al.* (1981).

Matrix grains often show very strong Lattice-Preferred Orientation (LPO), as visualized through the use of a gypsum plate (Fig. 5C,D) and documented by semiquantitative, photometric analyses (Price, 1973) (Fig. 5E). Along the ultra-thin edges of thin sections, LPOs can be seen to be coherent on the scale of a few

Fig. 5 Structural and microstructural observations in LK mylonites. (A) Left-hand side: complex structures observed in the LK from northern exposures include sheath folds, shear bands and 'crumpling' of the alternation of white, pure calcite and black, stylolitic layers. Sample from Piz Sardona (738.150/197.600). Right-hand side: Contact LK-Verrucano at Ringelspitz (745.200/195.800), the Verrucano is brecciated and cut by the septum consisting of a cataclasite (lower contact). (B) Glarus thrust at Plaun Grond (730.3/192) with LK representative of southern localities. General banding in different colours results from strongly deformed light coloured veins, dark stylolites and traces of secondary dolomite responsible for the orange/yellow alteration colour at the LK-Verrucano (green) contact. (C) Ultrathin ($<$ 3 μm) edges of a LK thin section from Kärpf (726.3/196.95) display strong lattice-preferred orientation visualized through the use of a gypsum plate (530 nm) and crossed polarizers. Note horizontal banding. (D) Close-up of the same sample as shown in (C). Average grain size of matrix calcite is less than 3 μm; note fairly straight grain boundaries and the absence of a shape preferred orientation. The large ameboid orange grain possibly represents the relic of a former vein. (E) Photometrically determined rose diagram illustrates the preferred orientation of calcite *c*-axes (projected onto the plane of observation) measured in six different spots with 200 μm diameter along the ultrathin edge of the section shown in C. (F) Cold cathodoluminescence reveals the presence of an old and sheared ghost vein in the calc-mylonite sample from the Grau Berg locality (South). Three successive generations of veins are easily distinguished in CL. Dark red grains along the second vein are quartz. (G) Same thin section as F, seen in normal light, displays a homogeneous fine-grained calcite matrix in the places where CL reveals the presence of ghost vein.

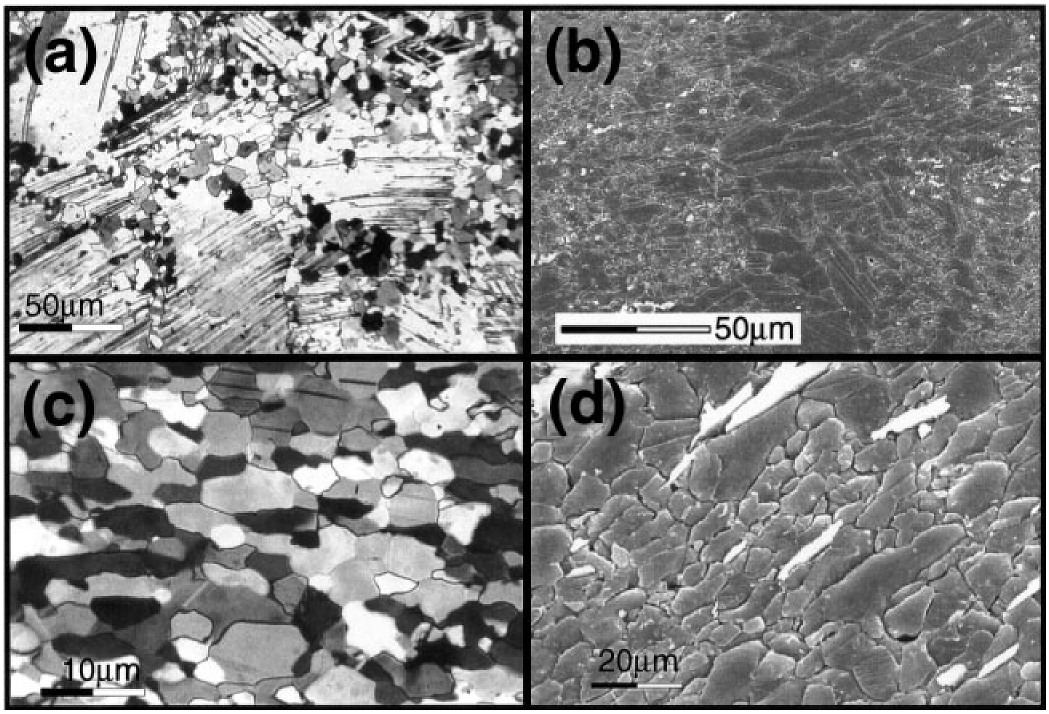


Fig. 6 (a) Heavily twinned coarse calcite grains of veiny origin. Recrystallized 'matrix' grains nucleate along twin- and grain-boundaries resulting in a mortar texture. Sample from Kärpf (726.250/197), thin section view, crossed polarizers. (b) idem, SEM view. (c) Shape-preferred orientation in an LK sample from Vorab Pign (732.25/192.525), southern part of the Glarus thrust, thin section view, crossed polarizers. (d) idem, SEM view.

millimetres across domains with very fine-grained matrix and coarser grains. No Shape-Preferred Orientations (SPO) could be detected in the very fine-grained matrix in the north, whereas weak SPO with mean axial ratios of up to 2 are developed in the south (Fig. 6c,d).

Cathodoluminescence on thin sections

In cold cathodoluminescence (CL), calcite appears in various shades of orange and yellow as a consequence of minute substitutions of Ca^{2+} by Mn^{2+} and the presence of other trace elements (Barbin and Schvoerer, 1997). CL microscopy reveals the presence of an unexpected composite layering within optically homogeneous veins. Most interestingly, CL provides evidence for completely recrystallized 'ghost' veins within the ultrafine-grained matrix (Fig. 5F,G). Optically nondetectable, such ghost veins apparently preserved some subtle geochemical vein signature despite intense folding and shearing and associated dynamic recrystallization. Diffuse boundaries (Fig. 5F,G) of such ghost veins are thought to be the result of chemical diffusion associated with GBM (Hay and Evans, 1987).

Discussion and conclusions

Based on experimental data and the absence of clear LPOs within LK mylonite samples, Schmid proposed grain boundary sliding (superplastic flow) as the dominant deformation mechanism to account for the extreme strain localization observed at the base of the Glarus thrust (Schmid *et al.*, 1977; Schmid *et al.*, 1981; Schmid, 1982a). In this interpretation, the LK is considered a very weak décollement layer on which the Glarus nappe was translated as a rigid block. Burkhard *et al.* (1992) provided stable isotope evidence for considerable fluid advection during thrusting and therefore speculated about the role of such fluids in deformation (cf. Bowman *et al.*, 1994). Meso- and microstructural observations document the alternating activity of brittle and crystal-plastic deformation processes and the omnipresence of dissolution-crystallization processes. These observations are difficult to reconcile with the idea of a single, dominant deformation mechanism such as the superplasticity proposed by Schmid *et al.* (1977, 1981) and Schmid (1982a). Brittle deformation features have been noted by earlier authors (Heim, 1921; Schmid *et al.*, 1981; Pfiffner, 1982) but generally such observations were discarded as unimportant, late overprinting. However, there is no evidence for an evolution from plastic to brittle deformation with time. Foliated gouge textures and overprinted vein bands are more obvious in northern than southern localities. This, however, can be interpreted in terms of a temperature gradient up-dip, rather than reflecting an evolution through time. Ductile deformation and dynamic recrystallization were merely more efficient in wiping out the evidence for brittle deformations further south, rather than being more important in terms of their contribution to total strain and thrust translation.

The absence of LPOs was a central argument used by Schmid *et al.* (1977) in favour of superplasticity. The present observations of strong LPOs seen in optical microscopy (Fig. 5C–E) contrast with the lack of LPOs in the XRD-samples analysed by Schmid *et al.* (1981). It could be argued that these optically visible LPOs are a local phenomenon, inherited from other LPOs resulting from twinning of some coarse vein grains that have totally recrystallized. However, according to Walker *et al.* (1990), grain boundary sliding in the fine-grained matrix, should not allow the preservation of strong LPOs. Alternatively, when measured integrally on large (cm-size slides) by XRD techniques, LPOs may be 'diluted' by the rotation of mm- to cm-size rock fragments, which are apparent in the form of 'chaotic' foliated gouge textures (Figs 4b, 5A).

The Glarus thrust roots at mid-crustal levels (Pfiffner, 1985). Dewatering by compaction and prograde metamorphism in the footwall produce considerable amounts of fluids with a general tendency to escape upward towards the foreland (Oliver, 1986; Marquer and Burkhard, 1992). The role of such fluids in deformation depends critically on the fluid production rate and permeability in the surrounding rock masses (Connolly and Thompson, 1989; Gueguen *et al.*, 1991). It is proposed herein that an abrupt change in permeability between the footwall and hanging wall lead to fluid channelling at this particular thrust contact. In this scenario, fluids produced in the footwall percolate continuously upward, preferentially along the steeply inclined pre-existing (Calanda phase) foliation. The clay-rich Verrucano thrust sheet, with actively forming subhorizontal foliation, represents a permeability barrier to this percolation. In analogy to the fault-valve scenario (Sibson, 1990), fluid pressures would increase below this contact up to the threshold for hydrofracturing associated with seismic slip (Sibson, 1990; Petit *et al.*, 1999). As a result of dilatency, fluid pressures would drop abruptly to values lower than within wall rock. Healing of the fracture network and formation of veins would progressively seal the thrust fault, allowing fluid pressures to build up again. Between fracture events, ductile intracrystalline deformation and dynamic recrystallization would result in the formation of a microcrystalline matrix within the LK and of LPOs within this matrix. Thrust faults do not have the ideal orientation for such fault-valve behaviour (Sibson, 1990; Nguyen *et al.*, 1998). However, similar structural observations and interpretations have been reported from other thrusts in the Apennines (Coli and Sani, 1990), the McConnell thrust in the Canadian Rockies and the Hunter Valley thrust in the Appalachians (Kennedy and Logan, 1997; Kennedy *et al.*, 1998), and the Gavarnie thrust in the Pyrenees (McCaig *et al.*, 1995).

The paradox of the lobate–cuspate contact, which suggests a competent LK sandwiched in between less comptetent Verrucano and flysch, finds an elegant solution in the fault-valve/seismic failure scenario. Fracturing and calcite mineralizations along the base of the Verrucano thrust sheet are triggered by fluctuations in fluid pressure, because fluids are stored below this 'permeability barrier'. The planar septum horizons, cataclasites and veins reflect some of the latest brittle events. Background deformation of the entire thrust zone in the ductile regime is responsible for the repeated shearing and folding of older septums, veins and the LK–wall rock contacts, as well as mylonitization of the Verrucano and folding of the topmost metres of flysch. The relative contributions of seismic and plastic deformation to the total thrust translation are difficult to evaluate. In the present interpretation, the thrust translation was accommodated mostly by numerous seismic slip events. In summary, the Glarus nappe with its enigmatic LK, is a good candidate for a major thrust fault which owes its localization and apparent softening to transiently near lithostatic fluid pressures (Etheridge *et al.*, 1984; Carter and Dworkin, 1990; Carter *et al.*, 1990; Henry and Le Pichon, 1991), rather than to the presence of a permanently weak décollement lithology.

Acknowledgements

We would like to thank F. Gainon, N. Challandes and A. Aubry for their help with field work and sampling; K. Ramseyer for CL imagery. A. M. McCaig and R. Abart are thanked for stimulating discussions and active collaboration. We acknowledge thorough and constructive reviews by S. M. Schmid and B. den Brok. This study is supported by the Swiss National Science Foundation Grants 20-50535.97 and 20-56920.99.

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Received 19 November 1999; revised version accepted 27 February 2001