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Fluid flow and rock alteration along the Glarus thrust

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Key words: Glarus thrust, rock alteration, strain localization, Lochseiten calc tectonite

ABSTRACT

Chemical alteration of rocks along the Glarus overthrust reflects different stages of fluid rock interaction associated with thrusting. At the base of the Verrucano in the hanging wall of the thrust, sodium was largely removed during an early stage of fluid-rock interaction, which is ascribed to thrust-parallel fluid flow in a damage zone immediately above the thrust. This alteration leads to the formation of white mica at the expense of albite-rich plagioclase and potassium feldspar. This probably enhanced mechanical weakening of the Verrucano base allowing for progressive strain localization. At a later stage of thrusting, fluid-mediated chemical exchange between the footwall and the hanging wall lithologies produced a second generation of alteration phenomena. Reduction of ferric iron oxides at the base of the Verrucano indicates fluid supply from the underlying flysch units in the northern section of the thrust. Fluid supply from the footwall may have kept pore fluid pressure close to lithostatic and enhanced cataclastic deformation. The chemical characteristics of the Lochseiten calc-tectonite suggest its derivation from Mesozoic limestone. In the southern sections of the thrust, the major element and stable isotope compositions show continuous trends from the Cretaceous limestone in the footwall of the thrust up to the contact with the Verrucano, indicating that the calc-tectonite developed due to progressive deformation from the footwall units. In the northern sections of the thrust, the Lochseiten calc-tectonite has a distinct chemical and stable isotope signature, which suggests that it is largely derived from Infrahelvetic slices, i.e. decapitated fragments of the footwall limestone from the southern sections of the thrust, which were tectonically emplaced along the thrust further north. Only at the Lochseiten type locality the original chemical and stable isotope signatures of the calc-tectonite were completely obliterated during intense reworking by dissolution and re-precipitation.

DEDICATION

This work was planned and began in cooperation with Martin Burkhard. It was his enthusiasm and unlimited support that gave us the courage to address the processes that were active during formation of the magnificent Glarus thrust that Martin was so familiar with. After Martin passed away we not only miss a great scientist but we miss our friend. This contribution is devoted to Martin Burkhard.

Introduction

The Glarus thrust is a prominent tectonic feature in the Helvetic Alps of eastern Switzerland (Fig. 1). It is exposed as an exceptionally sharp horizon over an area of approximately 600 square kilometres. It is an out-of-sequence thrust, along which the ca. 10 km thick nappe stack of the Glarus nappe system was transported in a northward direction over the Infrahelvetic units during the early Miocene. The Glarus thrust has attracted geologists over more than 150 years and was the first overthrust to be recognized as such in the Alps (Bertrand 1884). For a brief review of these more than 150 years of geological research on the Glarus thrust, see Trümpy (1969, 1991). The geology (e.g. Oberholzer 1933; Trümpy 1980), structures (e.g. Heim, 1921; Schmid, 1975; Pfiffner, 1986) and metamorphism (e.g. Frey 1988; Rahn et al. 1995) are very well known. The magnificent structure of the Glarus thrust has also motivated a series of process oriented studies. For example, Hsü (1969) presented theoretical considerations on the mechanics of thrusting and Schmid (1975, 1982) proposed the mechanism of super-plasticity as a possible explanation for the pronounced strain localization along the thrust.

It has long been recognized that fluids may play a key role in rock deformation and may thereby influence tectonic processes. Fluid overpressure may dramatically lower friction during thrusting. This notion has been employed to explain the

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paradox of large overthrusts by Hubbert & Rubey (1959). In addition fluids under high (i.e. close to lithostatic) pressure may decrease the fracture strength of rocks (Price 1988). The presence of aqueous fluids may further drive hydration reactions, which can lead to the transformation of mechanically strong minerals (e.g., feldspar) into mechanically weak minerals (Raleigh & Paterson 1965; Murrell & Ismail 1976; Fitz Gerald & Stünitz 1993; Stünitz & Fitz Gerald 1993; Escartin et al. 1997).

The obvious relation between fluids and deformation motivated studies of potential fluid-rock interaction on the Glarus thrust. Systematic investigations of the fluid regime associated with movement along the Glarus thrust were initiated with the contribution of Burkhard & Kerrich (1990), who documented a regional trend of successive north to south oxygen isotope alteration of the Lochseiten calc-tectonite. The oxygen isotope trend was interpreted by Burkhard et al. (1992) and by Bowman et al. (1994) as an isotopic front that was produced by northward migration of ^{18}O depleted fluids along the thrust, which they envisaged as being part of a crustal scale fluid escape structure. Using a one-dimensional model, Bowman et al. (1994) derived time integrated volumetric fluid fluxes on the order of 5000 m^3/m^2 for northwards directed flow from the root zone to the foreland of the thrust. Abart et al. (2002) and Badertscher et al. (2002) investigated the possible influence of fluid mediated oxygen isotope exchange between the hanging wall and the footwall lithologies on the regional oxygen isotope trend of the Lochseiten calc-tectonite. Based on stable isotope patterns in several profiles across the thrust, they found that the regional oxygen isotope trend correlates with the change in footwall lithology from flysch in the northern section to Mesozoic limestone in the south. They argued that the regional oxygen isotope trend of the Lochseiten calc-tectonite may well be explained by local oxygen isotope exchange between the footwall and hanging wall lithologies. They suggest different fluid flow regimes for the northern and southern sections of the thrust. In the north, where the footwall lithology is dominated by Tertiary flysch units, a modest but consistent upward-directed fluid flow component is inferred. In contrast, only thrust-parallel fluid flow is proposed for the southern section of the thrust, where the footwall is represented by Mesozoic limestone. Abart et al. (2002) argued that the upward-directed fluid flow component in the northern section of the thrust may have caused high, close to lithostatic, fluid pressure at the thrust. This may have "lubricated" slip along the thrust and helped strain localization through the mechanical effects of high fluid pressure. Such a view is corroborated by the findings of Badertscher & Burkhard (2000), who also had previously proposed high, close to lithostatic fluid pressures based on the observation of abundant veins within the Lochseiten calc-tectonite, which they ascribed to transient stages of cataclastic deformation in the calc-tectonite.

The fact that the regional oxygen isotope trend correlates with the change in footwall lithology (Abart et al. 2002) suggests that this feature was imprinted on the Lochseiten calc-tectonite at a late stage of thrusting, when the regional structure had already developed close to its present day geometry. Similarly, the microstructural evidence for cataclastic deformation in the Lochseiten calc-tectonite (Badertscher and Burkhard 2000) relies on subtle features, which supposedly are quickly obliterated in the course of progressive deformation. Stages of crystal-plastic deformation in the calc-tectonite are evident from the mylonitic fabric, with grain size on the order of a few micrometres and from the crystallographic preferred orientation (Schmid 1975; Badertscher & Burkhard 2000; Pfiffner 1982; Ebert 2006; Ebert et al. 2007). Hence, both the stable isotope patterns and the microstructural evidence of cataclastic deformation in the Lochseiten calc-tectonite seem to reflect interplay between fluids and rock deformation at a relatively late stage of thrusting. These observations can, however, contribute little to the understanding of the processes that were operative during the earlier stages of thrusting.

In this paper we focus on the chemical and mineralogical alteration at the base of the Verrucano in the hanging wall of the thrust. In many places, alteration at the base of the Verrucano is evident in the outcrop from a change in colour over the lowermost one to two metres above the thrust. A first set of data on bulk rock compositions in a sampling profile across the Glarus thrust was presented by Burkhard and Kerrich (1990). They described a conspicuous decrease in the sodium content in Verrucano samples toward the thrust. Abart et al. (2002) and Abart & Ramseyer (2002) reported hydration and rock alteration at the base of the Verrucano at the Lochseiten locality and at Grauberg. In both these sampling profiles, a loss of sodium in the lowermost few decimetres of the Verrucano could be detected. It was ascribed to the serizitization of albite-rich plagioclase. The latter authors argued that the breakdown of feldspar and the concomitant formation of sheet silicates may have promoted strain localization in the lowermost Verrucano. In this paper we further explore this potential effect of rock alteration at the base of the Verrucano on movement along the Glarus thrust. We present new geochemical data from six sampling profiles across the southern, central and northern sections of the thrust. We distinguish between relatively early and late alteration features and compare them to observed mineralogical and stable isotope trends. Finally we use the geochemical trends across the thrust to discuss various aspects of the genesis of the Lochseiten calc-tectonite.

Geological setting

The Helvetic realm comprises a fold and thrust belt, which forms the northern external tectonic units of the Swiss Alps. The Helvetic nappes are primarily composed of sediments that were derived from the Mesozoic shelf of the southern passive margin of the European continent. The Helvetic nappes were formed during the Alpine collision of the Apulian and European continents, which started in the latest Eocene.

The Glarus thrust is a major tectonic feature in the Helvetic Alps of eastern Switzerland (Fig. 1). It separates the Helvetic nappes of the Glarus nappe system in the hanging wall of the thrust from the Infrahelvetic units in the footwall. The Helvetic nappes are a series of thin-skinned decollement nappes composed of Permian to Eocene sediments. The Infrahelvetic units comprise a crystalline basement (Aar massif) with its parautochthonous Mesozoic to Tertiary sedimentary cover, as well as allochthonous slices of South Helvetic (Blattengrat) and Penninic (Sardona) Units. The latter units were emplaced on the parautochthonous units (North Helvetic Flysch) during an Oligocene deformation phase, which is referred to as the Pizol phase (Pfiffner 1977). The entire Infrahelvetic complex was folded with associated penetrative deformation during the Upper Oligocene Calanda phase (Schmid 1975, Pfiffner 1977). The thrusting event, referred to as the Ruchi phase, occurred during the Early Miocene (Milnes & Pfiffner 1980) and represents the youngest major deformation event in the eastern Helvetic Alps. Some of the units of the Infrahelvetic realm had an original paleogeographic position to the south of units now comprising the Glarus nappe system above the Glarus thrust, documenting the out-of-sequence character of the Glarus thrust. The present day geometry of the thrust (Fig. 2) is influenced by regional scale arching and rotation (Rahn & Grasemann 1999) that may have been caused by shortening in the underlying basement coeval with the Grindelwald phase in central and western Switzerland (Burkhard 1988). North of the Lochseiten locality, the Glarus thrust plunges below topography. It is believed to merge with the basal Helvetic Säntis thrust (Schmid et al. 1996), on which higher Helvetic nappes are thrust over Late Oligocene to Early Miocene Molasse. Balanced cross sections suggest that the Glarus thrust extends to mid crustal levels some 20 km south of the southernmost exposures (Pfiffner 1992).

Over a large portion of the presently exposed section of the Glarus thrust, the hanging wall consists of the Permian Verrucano formation (Figs. 1, 2), which is a clastic series consisting predominantly of siltstones and shales with minor intercalations of conglomerates and volcanoclastic horizons. Several klippen of the hanging wall resting on the thrust plane provide excellent three-dimensional outcrops. In the southernmost exposures, Verrucano is thrust over parautochthonous Late Jurassic to Early Cretaceous limestone units of the Infrahelvetic realm. These units were folded during the Calanda phase. The Calanda fold structures in the footwall were decapitated along the sharp tectonic contact of the Glarus thrust. The decapitated carbonate units can be found

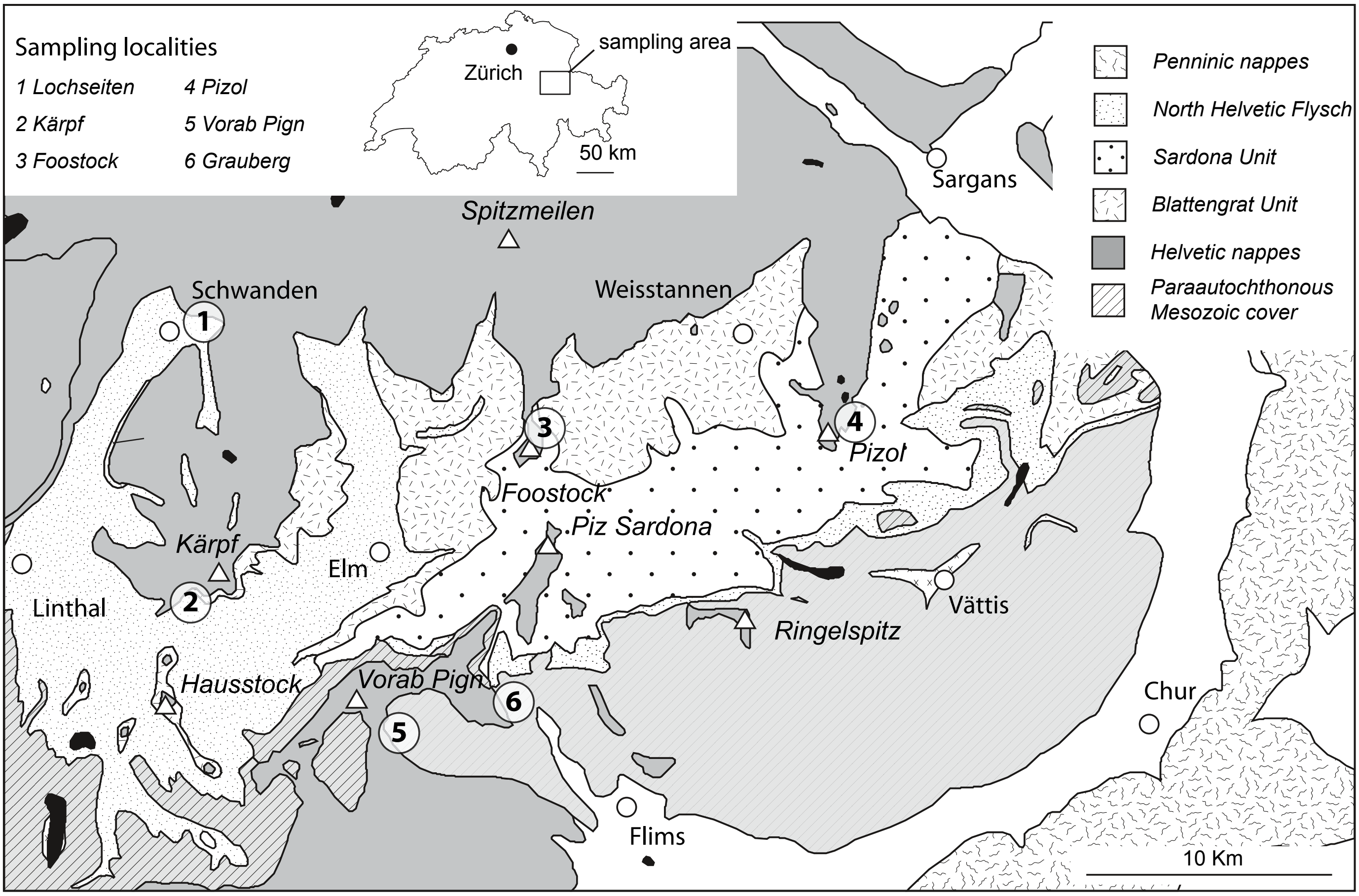

Fig. 1. Simplified tectonic map of the Glarus thrust, modified from Lihou & Allen (1996). Major sampling localities are labelled by numerals.

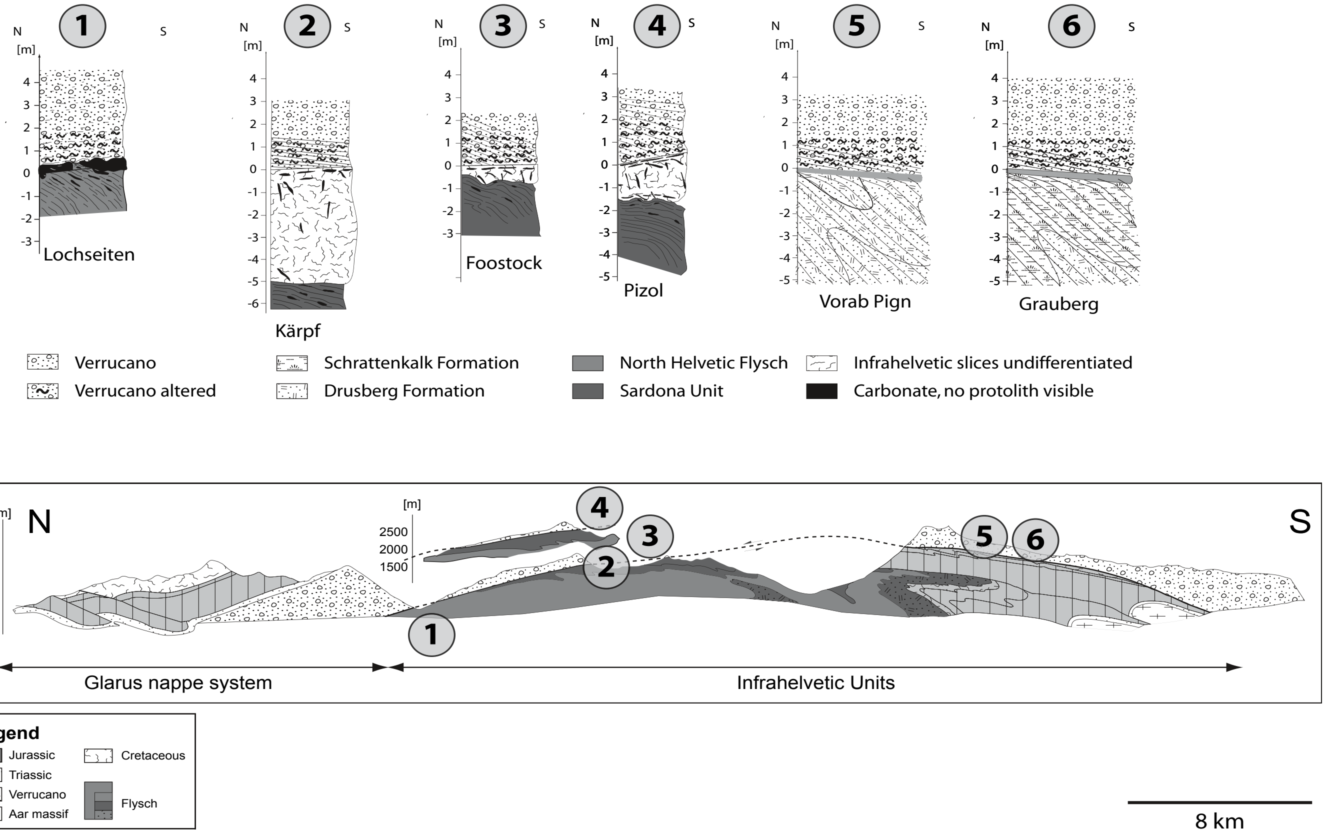

Fig. 2. Simplified N–S cross sections through the Glarus thrust with lithological columns for each of the major sampling localities described here.

further north as tectonic slivers with thicknesses ranging from a few decimetres to more than a hundred metres. They are sandwiched between the hanging wall and footwall units of the thrust and are referred to as "Infrahelvetic slices" (Fig. 3). North of the line Vorab Pign – Piz Segnes – Ringelspitz, the footwall of the thrust is represented by a sequence of Helvetic and Penninic Flysch units, which are up to 2 km thick and primarily comprised of marly slates, sandstones and conglomerates.

Metamorphic grade ranges from anchizonal (ca. 200 °C) in the north and in the footwall flysch to lower greenschist facies (350–380 °C) in the south and in the hanging wall (Frey 1988; Rahn et al. 1994). The anchi- to epizone boundary is offset along the Glarus thrust due to post-metamorphic thrusting (Rahn et al. 1995), and an inverse metamorphic gradient is documented across the thrust contact (Frey 1988). The Glarus thrust probably developed at a crustal depth of 10 to 15 km corresponding to lithostatic pressures of approximately 300 to 450 MPa. Metamorphism in the hanging wall was dated by Hunziker et al. (1986) and Hunziker (1987) at 30 to 34 Ma. Concordant K/Ar and Rb/Sr ages of illite (fraction <2 µm) from the Lochseiten locality indicate that thrusting was active till at least 23 Ma.

Fig. 3. View of the eastern face of Foostock. An Infrahelvetic slice of up to 150 m thickness and several 100 m length is sandwiched between Verrucano in the hanging wall and the Sardona Unit and Wildflysch in the footwall of the thrust. The slice pinches out toward the south and north. From macroscopic criteria it is believed to be derived from Schrattenkalk Formation, which was tectonically eroded from the Infrahelvetic units further south. The sampling profile Foostock is located at the northern tail of this Infrahelvetic slice, just outside the area of view on the right hand side.

Over large areas, the thrust plane is marked by a ca. 1 m thick calc-tectonite, the famous "Lochseitenkalk" (e.g. Heim 1921; Schmid 1975). Despite its vanishingly small vertical extent, the Lochseiten calc-tectonite is almost continuous over a distance of 15 km in a south to north transect and 25 km east to west. The genesis of the Lochseiten calc-tectonite has been controversial for more than a century. It was interpreted as an inverted and extremely thinned Mesozoic sequence by Heim (1878). In contrast, Rothpletz (1898) interpreted this strange unit as being due to "hydrothermal" mineralization.

The Lochseiten calc-tectonite shows evidence of intense deformation. It usually exhibits a finely laminated structure, with chaotic folding giving rise to the so-called "Knetstruktur" (Heim 1921). There is unambiguous evidence for deformation by both viscous and cataclastic mechanisms (Schmid 1975; Badertscher & Burkhard 2000; Ebert et al. 2007) reflecting the competition between deformation via crystal plastic deformation or diffusion accomodated creep and cataclastic flow and brittle fracturing (Schmid & Handy 1991). Irrespective of the dominating deformation mechanism, there is general agreement that the Lochseiten calc-tectonite accommodated most of the approximately 35 km displacement that can be reconstructed for the Glarus thrust from geologic relationships (Trümpy 1969).

Sampling strategy and analytical methods

Sampling localities were chosen to cover all different types of footwall-hanging wall-Lochseiten calc-tectonite relationships and to allow sampling over distances of at least several metres into both footwall and hanging wall lithologies. The positions of sampling localities are indicated in Figures 1 and 2. To allow for high spatial resolution, small sample volumes of about 5 cm^3 were taken. Major elements were analyzed by means of X-ray fluorescence spectroscopy using a Siemens SRS-3000 at the University of Basel. Fe_2O_3 was measured as $Fe_{Total.}$ ferric/ferrous iron ratios were determined using a modified Wilson method (Wilson 1960) at the Centre d'Analyses des Roches et de Mineraux (CAM) at the University Lausanne. Volatiles H_2O, CO_2, C_{org} and sulphur were analyzed using a LECO RC 412 combustion analyzer at the University of Basel. Selected element concentrations are shown in Figures 6 to 9. Carbon and oxygen isotope analyses were done on a Thermo Finnigan MAT 253 instrument using Gas Bench at Free University Berlin.

Sampling Profiles

Lochseiten

The Lochseiten locality is located at Swiss coordinates 725630/206425. At Lochseiten the hanging wall consists of red Verrucano and the footwall is represented by North Helvetic Flysch. These two lithologies are separated by the Lochseiten calc-tectonite. The North Helvetic Flysch comprises carbonate-bearing siltstones and shales, which exhibit progressively more intense calcite veining toward the thrust. The calcite veins are either sub-parallel to the steeply south-dipping foliation or become rotated into the thrust plane. The Lochseiten calc-tectonite is 0–40 cm thick. It shows a finely laminated structure, with chaotic folding and a "kneaded structure" ("Knetstruktur", Heim 1921) in its lower portion and a largely thrust-parallel foliation in the upper section. The contact with the flysch in the footwall shows a lobate-cuspate structure, where the flysch forms cusps into the calc-tectonite. This would suggest that the calc-tectonite was more competent than the flysch unit at the time of formation of the lobate-cuspate structure (e.g. Ramsay & Huber 1987, fig. 19.14). The contact to the Verrucano is comparatively smooth. The Lochseiten calc-tectonite is crosscut by a thrust parallel planar feature, which is referred to as the "septum" (Heim 1921). The septum is filled with a fault gouge which is up to 5 cm thick and comprised of clay minerals. The Verrucano in the hanging wall is comprised of abundant lithic fragments in a silty matrix. Away from the thrust, the Verrucano has a red colour and a weak foliation. However, in the lowermost 2 m above the thrust, the Verrucano changes to a green colour and develops a pronounced foliation. At the base of the Verrucano, the main foliation is crosscut at a large angle by abundant sub vertical carbonate-bearing veins. The sampling profile at Lochseiten consists of flysch samples from as much as 1.6 m below the septum, up to Verrucano samples at a position of 7.5 m above the septum.

Pizol

This Pizol sampling locality is located at Swiss coordinates 748945/202940. A view of the outcrop is shown in Figure 4. The footwall is represented by sandstones and siltstones of the Sardona unit. As at the Lochseiten locality, calcite veining becomes more pronounced toward the thrust. The Verrucano is represented by metamorphic sediments containing plagioclase, potassium feldspar, and white mica with minor components of chlorite, hematite, and calcite. The Verrucano is foliated with a stretching lineation in a N-S direction. The Verrucano and the flysch are separated by an approximately 2 m thick layer of carbonate with a yellow weathering colour. The macroscopic characteristics of this carbonate suggest that it was derived from Schrattenkalk Formation and should, therefore, be referred to as an Infrahelvetic slice. The carbonate is strongly tectonized, showing evidence of fracturing and veining. The veins appear to be progressively reoriented into parallelism with the thrust in the upper portion, giving rise to a slight lamination towards the contact with the Verrucano. The carbonate is dolomitized, so that the MgO content is substantially higher than in the presumed protolith. The transition to the Verrucano is sharp with only a few millimetres of fault gouge developed at the immediate contact. The sampling profile at Pizol starts at about 7.3 m below the base of the Verrucano and ends at 14 m above the Verrucano base.

Foostock

The sampling profile at Foostock is located at the northern tail of a large Infrahelvetic slice (Fig. 3) at Swiss coordinates 737900/202513. At this location, the footwall lithology consists of a layered sequence of sandstones with conglomeratic and carbonate-bearing layers. As at the Lochseiten and Pizol localities, calcite veins become progressively more abundant in the uppermost portion of the footwall. The calc-tectonite sandwiched between the footwall and the hanging wall is about 40 cm thick in this outcrop. It can be followed continuously and seems to be connected to the 150 m thick Infrahelvetic slice at the eastern face of Foostock, a few 100 m further south. The Verrucano in the hanging wall is foliated, with the foliation dipping steeply towards SSE, and thus clearly discordant to the thrust plane in this outcrop. The sampling profile at Foostock comprises samples from as much as 3.4 m below the Verrucano base to up to 8 m above its base.

Kärpf

The sampling profile at Kärpf is located at Swiss coordinates 725015/197090. This outcrop is quite similar to the one at Foostock in terms of lithology. The Verrucano seems, however, to contain a higher proportion of chlorite giving rise to a green colour. The calc-tectonite is about 2.5 m thick. In the uppermost 5 cm it shows a thrust-parallel lamination. The calc-tectonite develops a yellow colour towards the contact with the Verrucano, indicating dolomitization from above.

Vorab Pign

The sampling profile at Vorab Pign is located at Swiss coordinates 733653/188347. Here the footwall is represented by Cretaceous limestone units comprising the sequence from Kieselkalk to Schrattenkalk. The limestones were intensely folded during the Calanda phase of deformation, with amplitudes and wavelengths of ca. 10 m. The folds are supposedly parasitic to larger fold structures of the parautochthonous Mesozoic cover of the Aar massif. In the sampling profile (Fig. 5), the footwall is represented by the Drusberg Formation. The Drusberg Formation has a dark grey colour and shows a pronounced foliation parallel to the axial plane of the Calanda folds, which dips steeply toward SSE. Only in the uppermost 15 cm below the thrust does the foliation curve into a thrust-parallel orientation. In the uppermost portion below the thrust, the Drusberg Formation develops a yellow colour and shows fine lamination. The change in colour is sharp on the small (mm) scale, but on a larger (dm) scale the boundary between grey and yellow limestone is rather irregular. Although this boundary is quite conspicuous in outcrop, it does not appear to be a lithological or a structural boundary. The Verrucano is rather fine grained and shows a pronounced foliation, which is sub-parallel to the thrust, or transected by the thrust at a low angle. In the lowermost metre of the Verrucano, abundant fine calcite-ankerite veins with a brown weathering colour are present. The sampling profile at Vorab Pign comprises Drusberg Formation samples from as low as 2.5 m below the base of the Verrucano to up to 11 m into the Verrucano above.

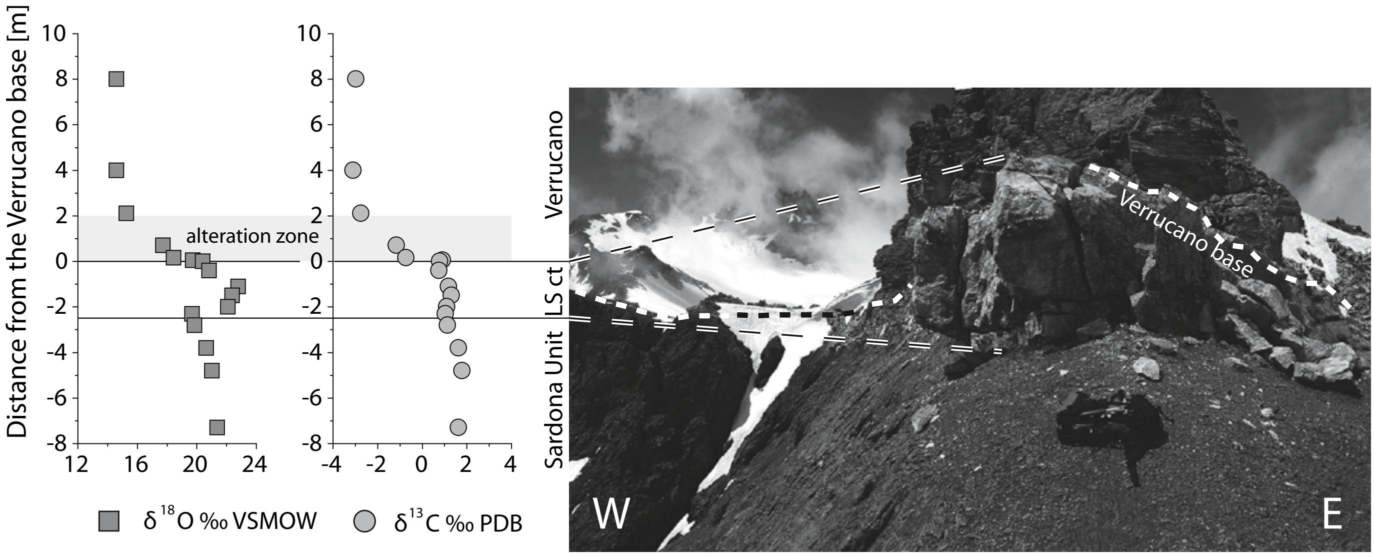

Fig. 4. Stable Isotope data from the sampling profile at Pizol, together with a view of the outcrop from the east. Dashed lines indicate the base and top of the Lochseiten calc-tectonite, which is about 2 m thick in this outcrop. The footwall is represented by siltstones and sandstones of the Sardona Unit, the hanging wall is represented by a quartz-feldspar rich variety of the Verrucano formation. Note that the oxygen isotope compositions of the Lochseiten calc-tectonite are higher than the $\delta^{18}O$ values of the carbonates in the underlying flysch and in the Verrucano hanging wall. This indicates that the Lochseiten calc-tectonite at Pizol was derived from a marine carbonate and emplaced in its present position relatively late, after the flysch and the Verrucano had exchanged and homognized their oxygen isotope signatures.

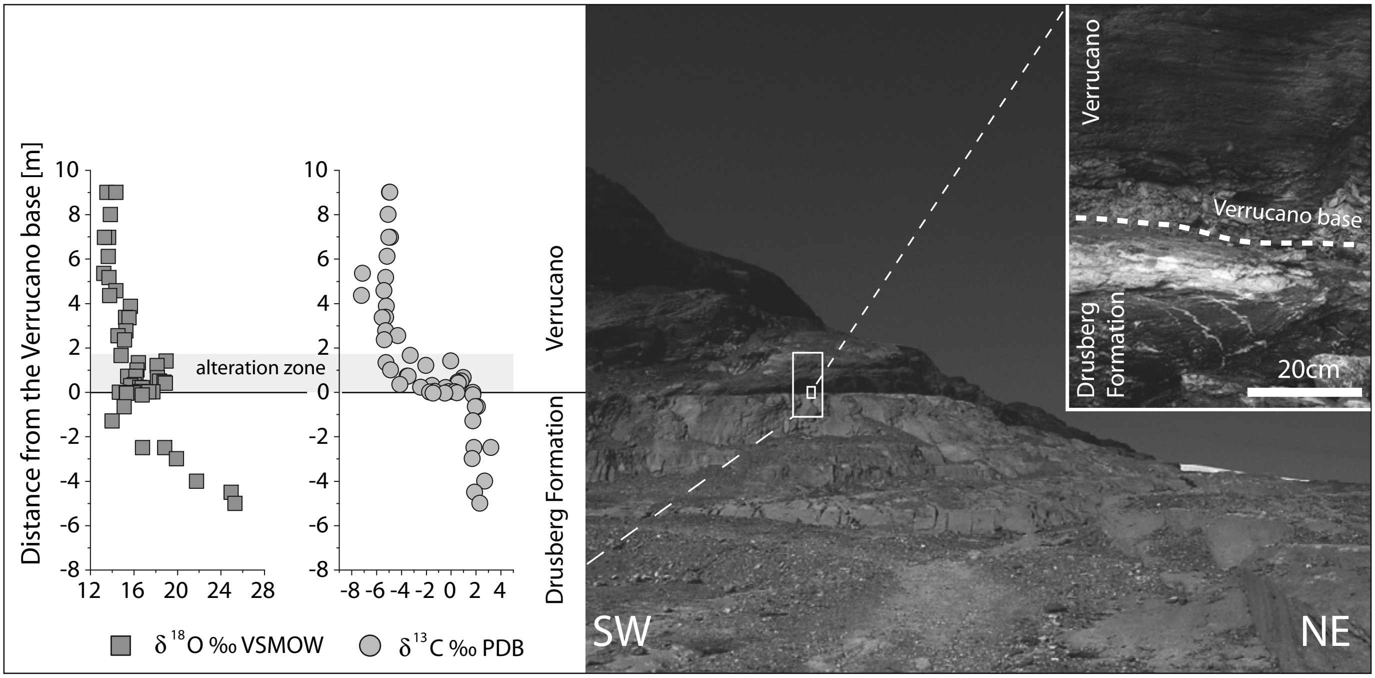

Fig. 5. Stable Isotope data from the sampling profile at Vorab Pign, together with a view of the outcrop form the SE. Inset at the upper right shows the uppermost portion of the Drusberg Formation, which loses its pigmentation in the uppermost 20 cm below the thrust. In this outcrop, the light grey to yellow coloured uppermost portion of the Drusberg Formation is referred to as the Lochseiten calc-tectonite.

Grauberg

The Grauberg sampling profile (Swiss coordinates 736.250/192.700) is located about 2 km northwest of Segnashütte, at an elevation of 2300 m above sea level. This exposure consists of a ca. 5 m vertical section of footwall limestones, a 25 cm thick layer of Lochseiten calc-tectonite and an over 100 m vertical section of the hanging wall Verrucano. The footwall consists of Lower Cretaceous massive grey limestones of the Schrattenkalk Formation. The latter is comprised of calcite (>95 vol.%) and minor amounts of quartz and muscovite. A pronounced foliation dipping about 30 to 40° SSE is ascribed to the pre-thrusting Calanda phase (Milnes and Pfiffner, 1980). In the uppermost metre below the thrust contact, this foliation is progressively rotated into a thrust-parallel orientation. Within this shear zone, the limestone is transformed to grey calc-mylonite with a planar, millimetre scale banding defined by the alternation of pure carbonate layers with more mica-rich layers and by layer-parallel calcite veins. The Verrucano is fine grained and shows abundant carbonate bearing veins at its base. It exhibits a pronounced foliation approximately parallel to the thrust.

Chemical alteration at the base of the Verrucano

Major elements

The Verrucano is lithologically heterogeneous and it is impossible to define a single representative reference composition for this unit. Even at a single outcrop, the apparently unaltered Verrucano may show pronounced compositional variability. Despite this problem, alteration trends could be detected in all outcrops over the lowermost metre of the Verrucano, where samples were taken at small intervals. Certain alteration trends are consistent over all the investigated sampling profiles. The concentrations of SiO_2, Al_2O_3, Na_2O, K_2O and CaO obtained from the six sampling profiles are shown in Figures 6 to 9. The concentrations of the minor elements such as TiO_2, MnO and P_2O_5 show a large scatter and are not considered further.

At the Lochseiten locality, silica concentrations are about 60 wt.% in the unaltered Verrucano and decrease to about 50 wt.% in the lowermost metre above the thrust (Fig. 6a). Al_2O_3 and K_2O concentrations increase over the same interval from background values of 15 wt.% and 5 wt.% to 20 wt.% and 6 wt.%, respectively. The most conspicuous trend is observed for sodium, the concentration of which decreases from background value of about 2 wt.% in the unaltered Verrucano to less than 0.5 wt.% immediately above the thrust. The CaO concentrations do not show any significant change in the lowermost Verrucano. Major element concentrations show a large scatter in samples from the North Helvetic Flysch from the footwall. The high content of carbonate is evident from CaO concentrations in the range of 20–40 wt.%. The Lochseiten calc-tectonite is almost pure limestone. The presence of sheet silicates is evident from slightly elevated Al_2O_3 and K_2O concentrations.

At Pizol, the composition of the unaltered Verrucano is relatively consistent at about 74 wt.% SiO_2, 13 wt.% Al_2O_3,

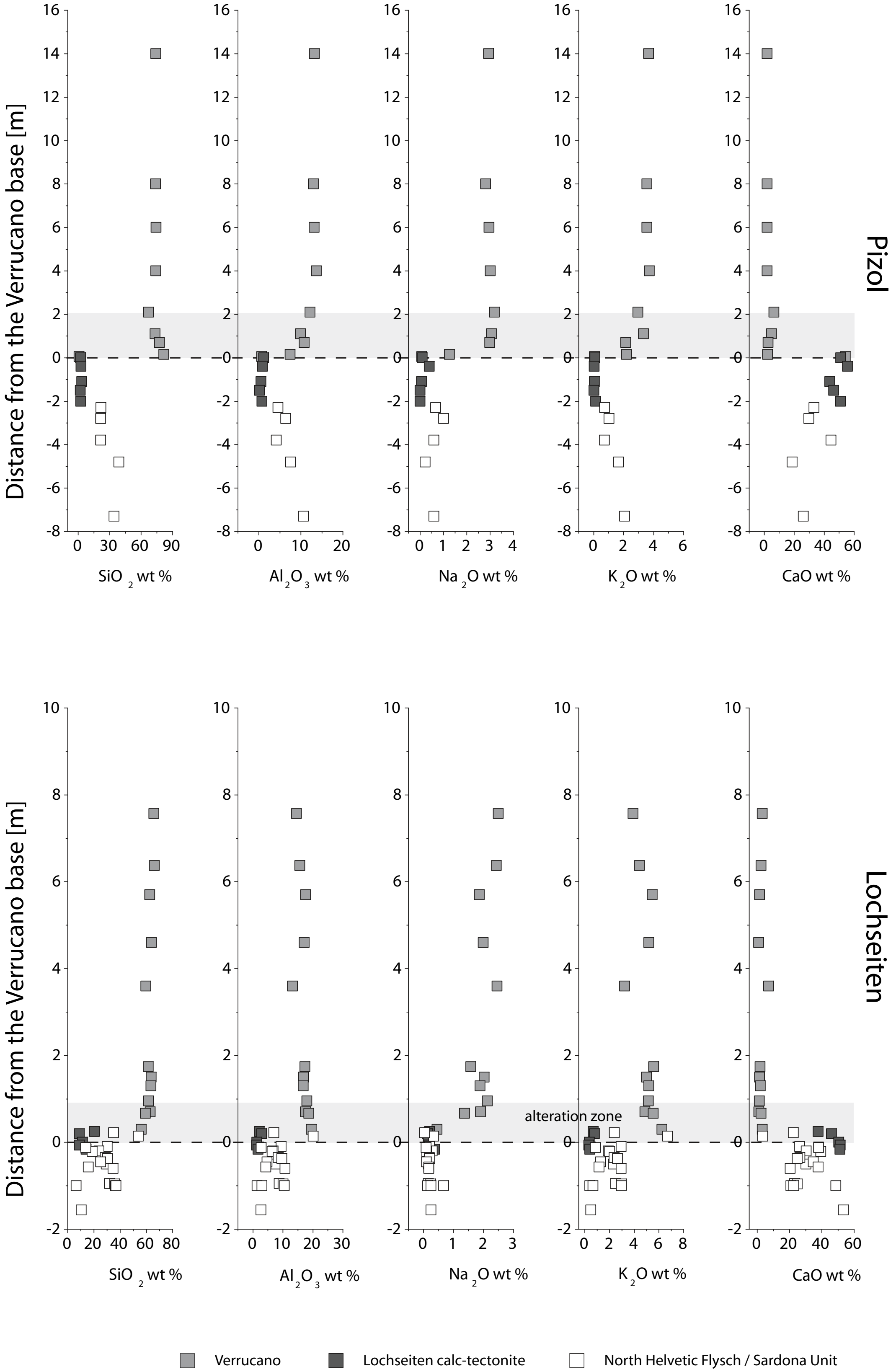

Fig. 6. Concentrations of selected oxide components in wt.% as determined from bulk rock samples by XRF spectroscopy. Sampling profiles are taken across the thrust (a) at Lochseiten locality, (b) at Pizol.

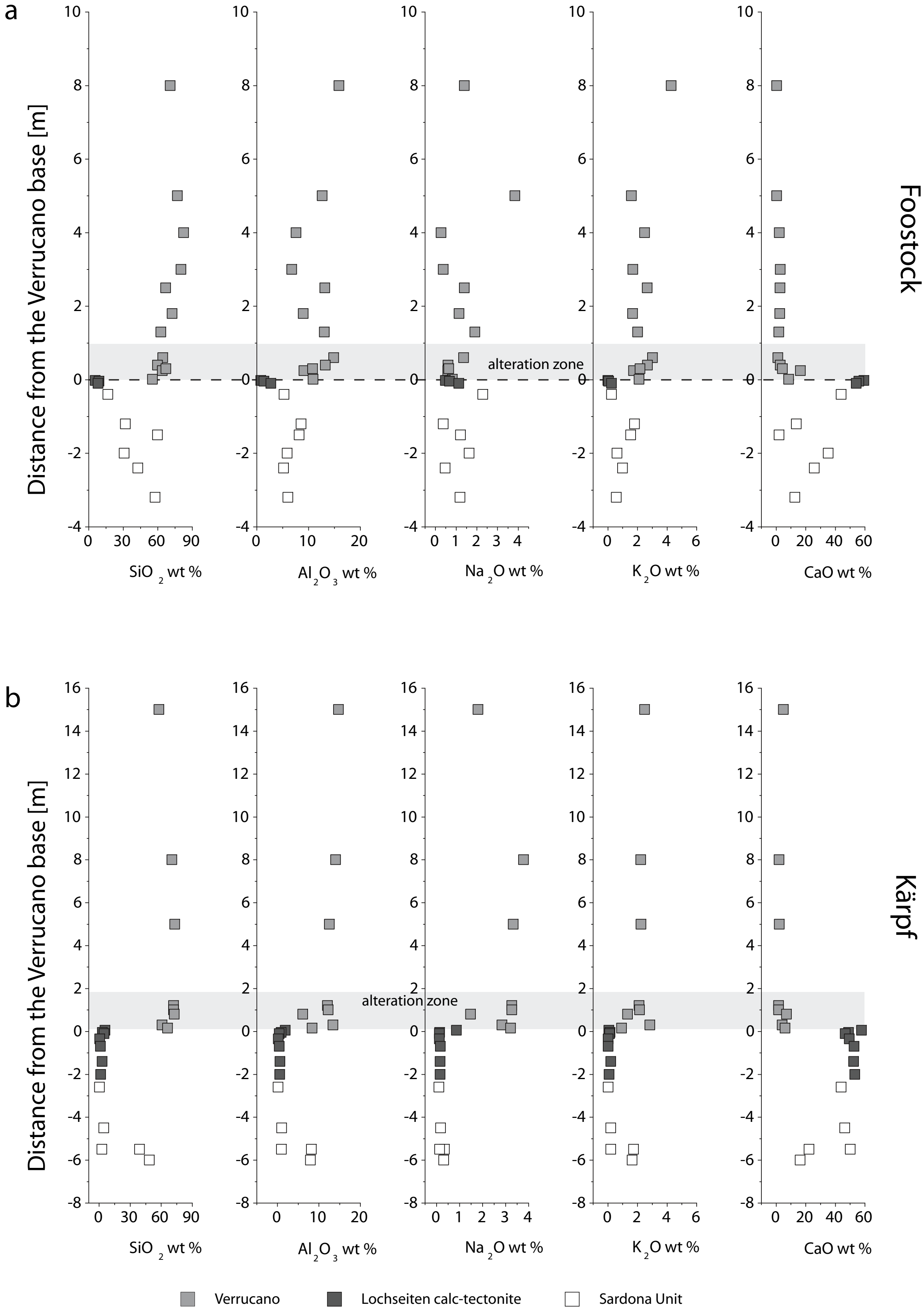

Fig. 7. Concentrations of selected oxide components in wt.% as determined from bulk rock samples by XRF spectroscopy. Sampling profiles are taken across the thrust (a) at Foostock, (b) at Kärpf.

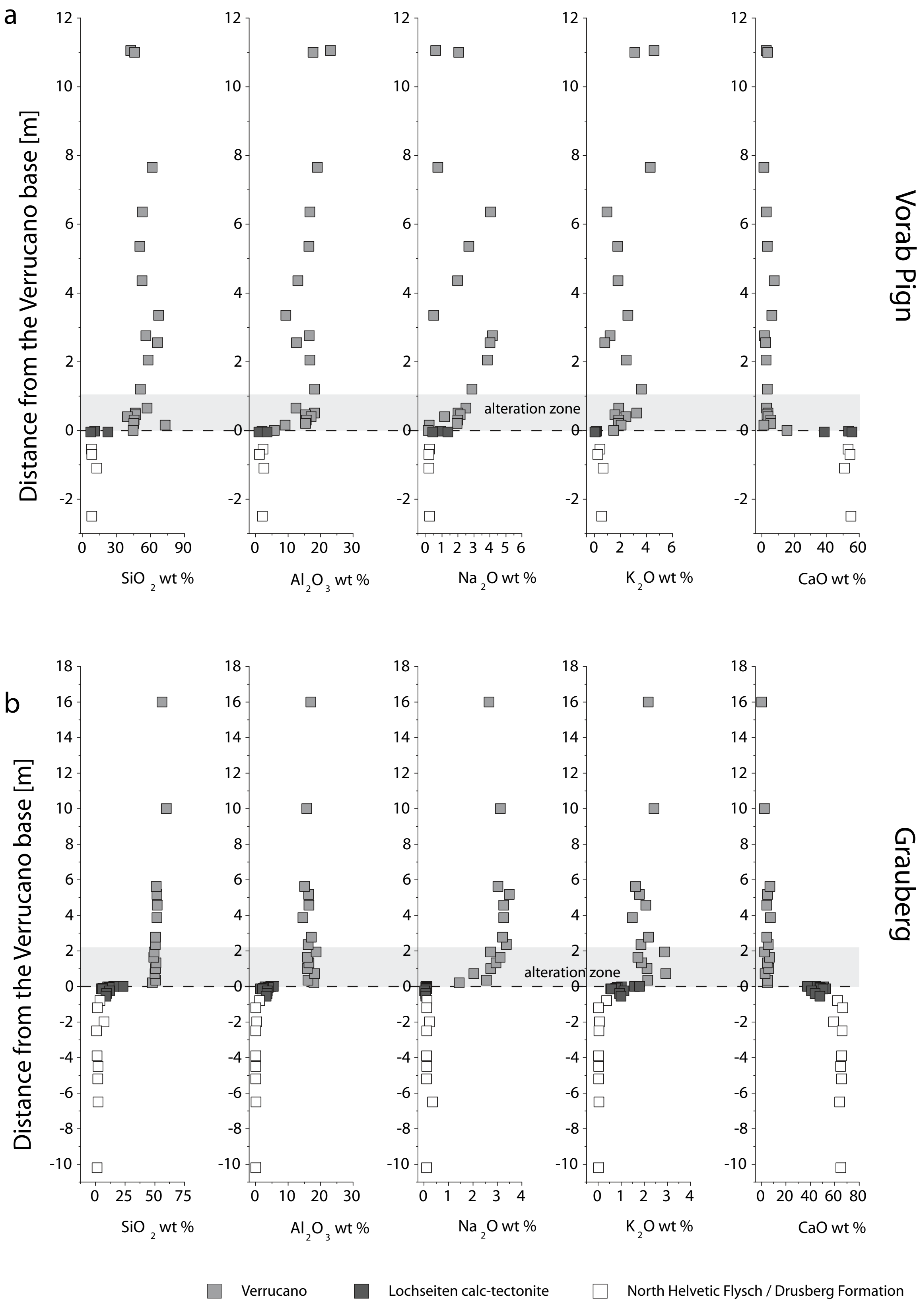

Fig. 8. Concentrations of selected oxide components in wt.% as determined from bulk rock samples by XRF spectroscopy. Sampling profiles are taken across the thrust (a) at Vorab Pign, (b) at Grauberg.

3.5 wt.% K_2O, 3.0 wt.% Na_2O and 2.0 wt.% CaO (Fig. 6b). In contrast to the Lochseiten locality, the SiO_2 concentration increases over the lowermost 2 m of the Verrucano to about 82 wt.%, and the Al_2O_3 and K_2O concentrations decrease concomitantly to about 7 and 2 wt.%, respectively. As at the Lochseiten locality, the most conspicuous alteration trend is observed for sodium, the concentration of which decreases to about 1.3 wt.% at the base of the Verrucano. The CaO concentrations remain constant. The Lochseiten calc-tectonite is an almost pure carbonate with a significant dolomite content, as evident from MgO concentrations of 7–17 wt.%. Again the flysch in the footwall is chemically rather heterogeneous. It has relatively high CaO contents in the range of 18–33 wt.%, and the CaO/MgO ratio is significantly higher in the flysch than in the Lochseiten calc-tectonite. The SiO_2 and Al_2O_3 concentrations are 21–39 wt.% and 4–11 wt.% respectively. The number of available data is too small to allow the identification of a systematic trend in bulk rock composition toward the thrust.

At Foostock, the unaltered Verrucano is chemically very heterogeneous, and identification of an alteration trend at its base is difficult (Fig. 7a). Nevertheless, we can still recognise alteration in the lowermost metre of the Verrucano, where samples that were taken at very short intervals define relatively smooth chemical trends. The Na_2O concentrations decrease systematically from 2.1 wt.% at 1.3 m above the thrust to 0.7 wt.% at the base of the Verrucano. The CaO concentrations increase from background values of about 1 wt.% to values of about 5 wt.% in the lowermost 30 cm of the Verrucano. SiO_2 and K_2O do not show any detectable trend. The flysch in the footwall is chemically very heterogeneous with SiO_2 contents varying between 17 and 58 wt.% and no systematic geochemical trends toward the thrust. The carbonate content is high, with CaO contents of up to 44 wt.%.

As at Foostock, the Verrucano at Kärpf is chemically very heterogeneous and alteration trends are hard to recognize (Fig. 7b). It is notable, however, that the CaO concentrations are somewhat elevated in the lowermost metre of the Verrucano. There the CaO concentrations are in the range of 4–7 wt.%, compared to background values of about 2 wt.%. The Al_2O_3 concentrations decrease concomitantly from about 12 wt.% in the unaltered Verrucano to 8 wt.% at its base. The SiO_2, Na_2O and K_2O contents remain constant. The composition of the flysch in the footwall is rather heterogeneous with SiO_2 contents in the range of 3 to 48 wt.% and no systematic chemical trend toward the thrust. The flysch is carbonate-rich, with CaO contents in the range of 16–45 wt.%. The Lochseiten calc-tectonite has a relatively low MgO content of about 1 wt.%. Only in the uppermost 30 cm towards the Verrucano does the calc-tectonite become progressively more dolomitized. There the MgO concentrations increase from about 1 wt.% at 70 cm below the Verrucano to slightly above 8 wt.% at the contact.

At Vorab Pign, the Al_2O_3 and Na_2O concentrations show a pronounced decrease at the bottom of the Verrucano (Fig. 8a). The Al_2O_3 contents decrease from background values in the range of about 15–20 wt.% down to 6 wt.% and the Na_2O contents decrease from background values of about 4 wt.% down to 0.2 wt.%. In contrast, the CaO contents increase from background values of about 3 wt.% up to 15 wt.% at the bottom of the Verrucano. The limestone in the footwall has a relatively high SiO_2 content in the range of 7–12 wt.%. No systematic chemical alteration trend is identified in the footwall limestone.

At Grauberg, the composition of the unaltered Verrucano can be relatively well defined, with SiO_2 contents of ca. 50 wt.%, Al_2O_3 ca. 17 wt.%, Na_2O ca. 3.5 wt.%, K_2O 1.5–3 wt.%, and CaO 0.5–7 wt.% (Fig. 8b). The sodium concentrations show a pronounced decrease from about 3.5 wt.% at about 2 m above the Verrucano base down to 1.5 wt.% at the base. It is interesting to note that the SiO_2, Al_2O_3, and K_2O concentrations show an increase in the uppermost 0.5 m of the limestone in the footwall of the thrust whereas CaO concentrations decrease concomitantly.

Ferric and ferrous iron

The systematics of the ferric and ferrous iron contents are substantially different in the northern and southern sections of the Glarus thrust (Fig. 9a). At the Lochseiten locality and at Pizol in the northern section of the Glarus thrust, the Fe^{3+}/Fe_{tot} ratios decrease from a background value of about 0.8–0.9 in the unaltered Verrucano to about 0.35 at the base of the alteration zone in the lowermost Verrucano. The Fe^{3+}/Fe_{tot} ratio at the base of the Verrucano is similar to that in the flysch in the footwall of the thrust. In contrast, the unaltered Verrucano is significantly more reduced at the Grauberg locality in the southern section of the thrust, where the background Fe^{3+}/Fe_{tot} ratio is about 0.35. At the base of the Verrucano, the Fe^{3+}/Fe_{tot} ratio increases to about 0.5. The Cretaceous limestone in the footwall is highly oxidized with a Fe^{3+}/Fe_{tot} ratio of about 0.6. It is interesting to note that at Lochseiten and Pizol, the Fe^{3+}/Fe_{tot} ratios measured in the Lochseiten calc-tectonite do not fit with the general trend from the relatively reduced flysch in the footwall to the relatively more oxidized Verrucano in the hanging wall. In contrast, at Grauberg there is a generally smooth transition between the relatively more oxidized limestone in the footwall and the relatively more reduced Verrucano in the hanging wall and the Fe^{3+}/Fe_{tot} ratios of the calc-tectonite are largely in accord with this general trend.

Sulphur

The sulphur contents are very low in the unaltered Verrucano samples, with concentrations of less than 0.1 wt.% (Fig. 9b). Only in the lowermost Verrucano do the sulphur concentrations increase to about 0.4 wt.% at Lochseiten and 0.15 wt.% at Pizol. In contrast, at Grauberg and Vorab Pign the sulphur contents remains constant in the lowermost Verrucano but elevated sulphur concentrations are observed in the uppermost portion of the Lochseiten calc-tectonite.

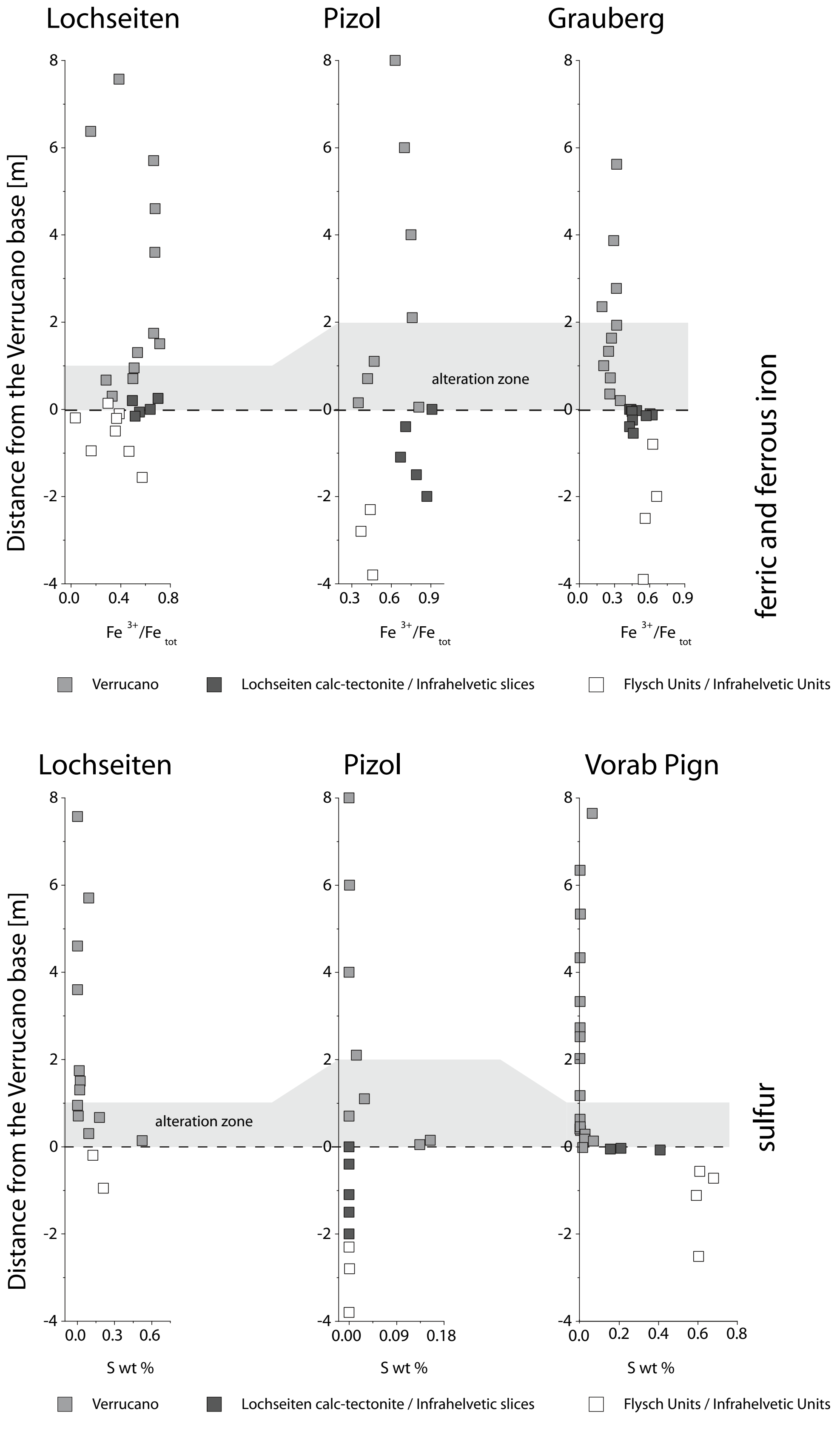

Fig. 9. (a) Sulphur concentrations (b) ferric/ferrous iron ratios at the Lochseiten, Pizol and Grauberg localitites.

Discussion

Alteration at the base of the Verrucano is observed everywhere in the presently exposed section of the Glarus thrust. In particular, a decrease in the sodium concentrations is consistently observed in all the investigated outcrops. This phenomenon appears to be independent of the footwall lithology. It may, therefore, reflect fluid-rock interaction associated with thrust parallel flow or alteration at an early stage of thrusting. At this time, the Glarus nappe system was still in a position further south, where the footwall had a different configuration than the present day geometry. We will refer to this stage of fluid rock interaction as the "early stage of fluid flow and rock alteration". In contrast, a second generation of alteration phenomena at the base of the Verrucano shows systematic differences between the northern and southern sections of the thrust. Whereas in the north the ferric/ferrous iron ratio increases from the flysch into the Verrucano, the Verrucano is reduced with respect to he footwall carbonate in the southern section of the thrust. Where the footwall is represented by flysch units, sulphur is enriched at the Verrucano base. In contrast, such enrichment is absent in the lowermost Verrucano and sulphur is enriched in the uppermost Lochseiten calc-tectonite, where the footwall is represented by Mesozoic limestone. The correlation of these alteration phenomena with the nature of the footwall lithology suggests that the redox conditions and systematics of the sulphur distribution were imprinted on the rocks after the present day geometry had already been attained. The sulphide minerals that grew during this alteration event impregnate the thrust related foliation in the lowermost Verrucano, which is defined by sheet silicates that were formed during the "early stage of fluid flow and rock alteration". This is why we refer to this alteration stage as the "late stage of fluid flow and rock alteration".

Early stage of fluid flow and rock alteration

Although there are differences in the details of the chemical alteration at the base of the Verrucano, certain trends are consistent in all investigated outcrops. In all sampling profiles, the Na_2O concentrations decrease substantially over the bottom 1–2 m of the Verrucano. In all but one sampling profile, the K_2O concentrations remain constant or decrease concomitantly but less strongly. Only in the sampling profile of Lochseiten does the K_2O concentration increase by about 1 wt.% at the base of the Verrucano. In several of the sampling profiles the CaO concentrations increase at the bottom of the Verrucano.

The decrease in alkali concentrations in the lowermost Verrucano cannot be explained by passive dilution due to the infiltration of carbonate from below. Such a process would imply constant element ratios amongst the alkali metals themselves, as well as between the alkali metals and cations other than calcium. However, element ratios vary substantially in profiles across the base of the Verrucano in all sampling profiles. This indicates selective addition or removal of individual components. The decrease in sodium may be readily explained by the dissolution of the albite component of plagioclase. This can be represented by the simplified reaction equation:

$$3\ NaAlSi_3O_8 + 12\ H_2O + 2\ H^+ + K^+ = KAl_3Si_3O_{10}(OH)_2 + 3\ Na^+ + 6\ H_4SiO_4$$

The mineralogical effect of this reaction is the formation of white mica at the expense of the albite component of plagioclase. Such a scenario is corroborated by petrographic observations and supported by calculated trends of modal mineral proportions (Fig. 10). At all three localities (Lochseiten, Pizol and Grauberg), the modal abundances of albite, K-feldspar and anorthite decrease in the alteration zone while the abundance of sheet silicates increases. Note that this reaction requires the introduction of water and protons and liberates silica. The potassium required for mica formation could be derived from the concomitant breakdown of potassium feldspar according to a reaction of the type:

$$3\ KAlSi_3O_8 + 12\ H_2O + 2\ H^+ = KAl_3Si_3O_{10}(OH)_2 + 2\ K^+ + 6\ H_4SiO_4$$

Again this is a hydration reaction that also consumes protons. Note that the stoichiometric equations are written in such a way that Al is conserved during reaction. This seems justified by petrographic observations, which indicate that white mica was indeed stable as feldspar was destabilized.

The Al_2O_3 depletion at the base of the Verrucano is probably due to the disappearance of chlorite. K_2O concentrations at the base of the Verrucano do not differ significantly from those in the unaltered portions further up. This indicates that the potassium that was liberated from the dissolution of potassium feldspar, as is evident in thin section, was retained due to the production of white mica. The increase in CaO content at the base of the Verrucano reflects carbonate impregnation and vein formation, with the most likely source of the carbonate being the underlying Cretaceous limestone in the southern section of the thrust and calcite saturated flysch in the north. On the whole, the alteration at the base of the Verrucano cannot be balanced locally with complementary alteration trends in the hanging wall and in the footwall in the present day geometry. We propose a combination of two processes to account for the observed geochemical trends. (1) Alteration at the base of the Verrucano may have started and largely occurred relatively early in the thrusting history, prior to the stage when the Verrucano was juxtaposed on top of the present day footwall units. A scenario, where alteration of the lowermost Verrucano was locally balanced by complementary alteration of the uppermost footwall units at an early stage of thrusting, when the present day geometry was not yet established, cannot be ruled out from the available data. From geological considerations, it appears that the footwall of the Glarus thrust was most likely comprised of lower Mesozoic sediments and/or Verrucano south of the presently exposed section of the thrust. It is hardly conceivable that any of these lithologies could drain sodium from the lowermost Verrucano. This is why we speculate that the mass transfer that caused alteration may have occurred

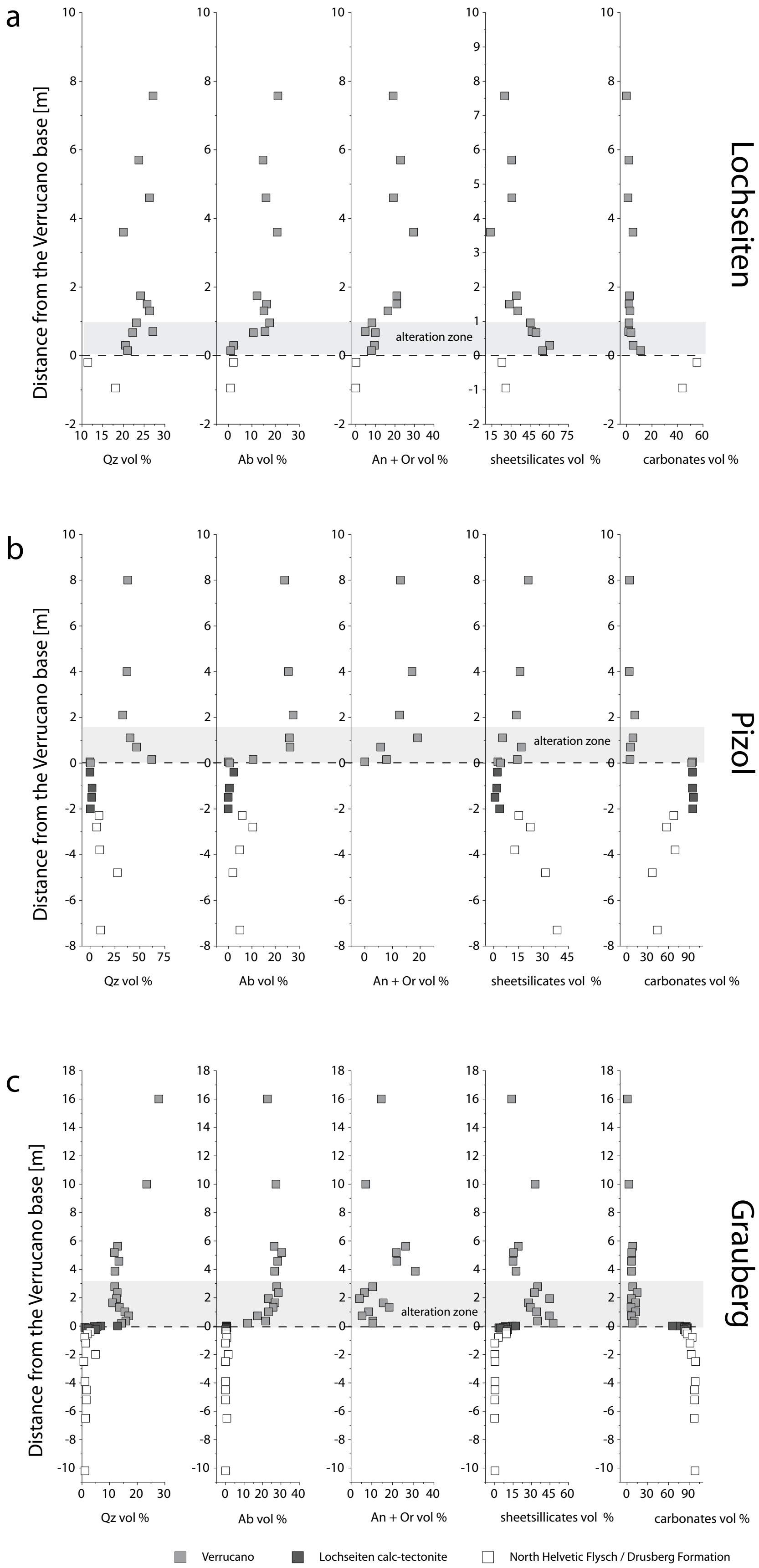

Fig. 10. Modal proportions of selected rock forming minerals as calculated from bulk rock compositions; (a) Lochseiten, (b) Pizol, (c) Grauberg.

during thrust-parallel fluid flow. In such a scenario, the alteration at the base of the Verrucano need not be locally balanced across the thrust at any stage and the sink for sodium needs to be sought further north, i.e., in the presumed direction of fluid flow. It is further proposed that thrust-parallel fluid flow largely occurred in a "damage zone" at the base of the Verrucano. This is suggested by the chemical alteration at the base of the Verrucano. It also appears rather unlikely that the entire fluid flux that is necessary to explain the chemical alteration at the base of the Verrucano could have been accommodated in the thin layer of the Lochseiten calc-tectonite. It is important to note that in quartz- and feldspar-rich lithologies of the Verrucano, the alteration zone correlates with a zone of intense deformation and development of thrust parallel foliation. This has been described in detail by Abart & Ramseyer (2002) for the Lochseiten locality, and it is well documented also for the sampling profile at Pizol (Fig. 11). This suggests that replacement of feldspar by white mica lead to a mechanical weakening of the lowermost Verrucano and allowed for strain localization.

Late stage of fluid flow and rock alteration

The ferrous/ferric iron ratios seem to be due to exchange of redox active agents between the base of the Verrucano and the footwall lithologies. As the type of alteration correlates with the nature of the footwall lithology this redox alteration appears to largely reflect the present day geometry, i.e., a late stage of thrusting.

Similar to the stable isotope trends that are documented in several sampling profiles across the thrust (Abart et al. 2002; Badertscher et al 2002), the observed changes in redox state indicate an upward-directed component of fluid flow for the northern section of the thrust. Given that ferrous iron is available in the system, chlorite may be formed, for example at the expense of smectite, by a reaction of the type:

$$\mathrm{Ca_{0.17}\,(Al, Mg, Fe)_2\,(Si, Al)_4\,O_{10}\,OH)_2 *n\,H_2O + 3\,Fe(OH)_2}$$
$$\mathrm{= (Al, Mg, Fe)_3\,(Si, Al)_4\,O_{10}\,OH)_2 * 3\,Fe(OH)_2 + 0.17\,Ca^{2+} + n\,H_2O}$$

In the Verrucano an obvious source for ferrous iron is the reduction of hematite according to a reaction of the type:

$$\mathrm{Fe_2O_3 + H_2O = 2\,Fe(OH)_2 + \tfrac{1}{2}\,O_2}$$

In combination, these mineral reactions consume hematite and produce chlorite, i.e. they contribute to the observed change in colour of the Verrucano from red, in the unaltered portions, to green in the alteration zone. It must be noted, however, that the reduction of ferric iron in the Verrucano is not necessarily related to processes associated with thrusting. In the southern section of the thrust, hematite has been reduced pervasively, probably during the metamorphic overprint associated with the Calanda phase of deformation. Only in the northern section of the thrust is this reduction confined to the damage zone above the thrust, indicating that a reducing fluid infiltrated from the underlying flysch, which contains abundant organic material (Frey 1988) and lends itself as a source for a reducing fluid.

At Grauberg in the southern section of the thrust, oxidation at the base of the Verrucano is less pronounced. This may either be due to the fact that no fluid was supplied from the footwall limestone, or it may reflect limited exchange between footwall and hanging wall by transversal dispersion associated with fluid flow along the thrust. Transversal dispersion describes the mixing of fluid due to flow along a tortuous flow path in a porous medium. Independent of mixing (diffusion) mechanisms that occur on the molecular scale, the difference in flow path length that results from the complex pore geometry of the porous medium, leads to mixing of the fluid. The effect of such mixing is the degradation of sharp tracer signals. It can't be distinguished from the effects of molecular diffusion. This mixing effect exists in the direction parallel to the overall flow direction (longitudinal dispersion) and perpendicular to the general flow direction (transversal dispersion).

It is interesting to note that at Pizol the Lochseiten calc-tectonite has higher ferrous iron content than the rocks in the hanging wall and in the footwall (Fig. 9a). This indicates that the Lochseiten calc-tectonite has preserved its oxidation state from a more oxidized source region, from where it was tectonically eroded and placed into its present position only at a late stage of thrusting, when the initial contrast in redox states that existed between the Verrucano and the flysch had already been eliminated. The view that reducing fluids were provided by the flysch in the footwall of the northern section of the thrust is also corroborated by the observation that sulphur is enriched at the base of the Verrucano at the Lochseiten and Pizol localities (Fig. 9b). Under reducing conditions, the solubility of sulphur is relatively high in an aqueous fluid. When a reducing fluid from the flysch migrates upward into the Verrucano, it will reduce ferric iron oxides such as hematite. During this process the fluid will become successively more oxidized. This leads to a reduction of sulphur solubility and induces precipitation of iron sulphides. The reduction of ferric iron oxides at the base of the Verrucano is evident from the change in colour from red to green at the base of the Verrucano. The localized precipitation of sulphides can be documented petrographically and is indicated by the elevated bulk rock sulphur contents at the base of the Verrucano.

Origin of the Lochseiten calc-tectonite

Based on field relations and geochemical data, we distinguish at least three ways by which the Lochseiten calc-tectonite may have developed. In the southern section of the thrust (Vorab Pign and Grauberg), the Lochseiten calc-tectonite seems to develop by progressive deformation from the Mesozoic limestone in the footwall of the thrust. A progressive mylonitization of limestone in the footwall of the thrust was described for the Grauberg locality by Abart et al. (2002) and was investigated in detail by Ebert et al. (2007). Based on grain size analysis, the latter authors distinguish between an early high temperature

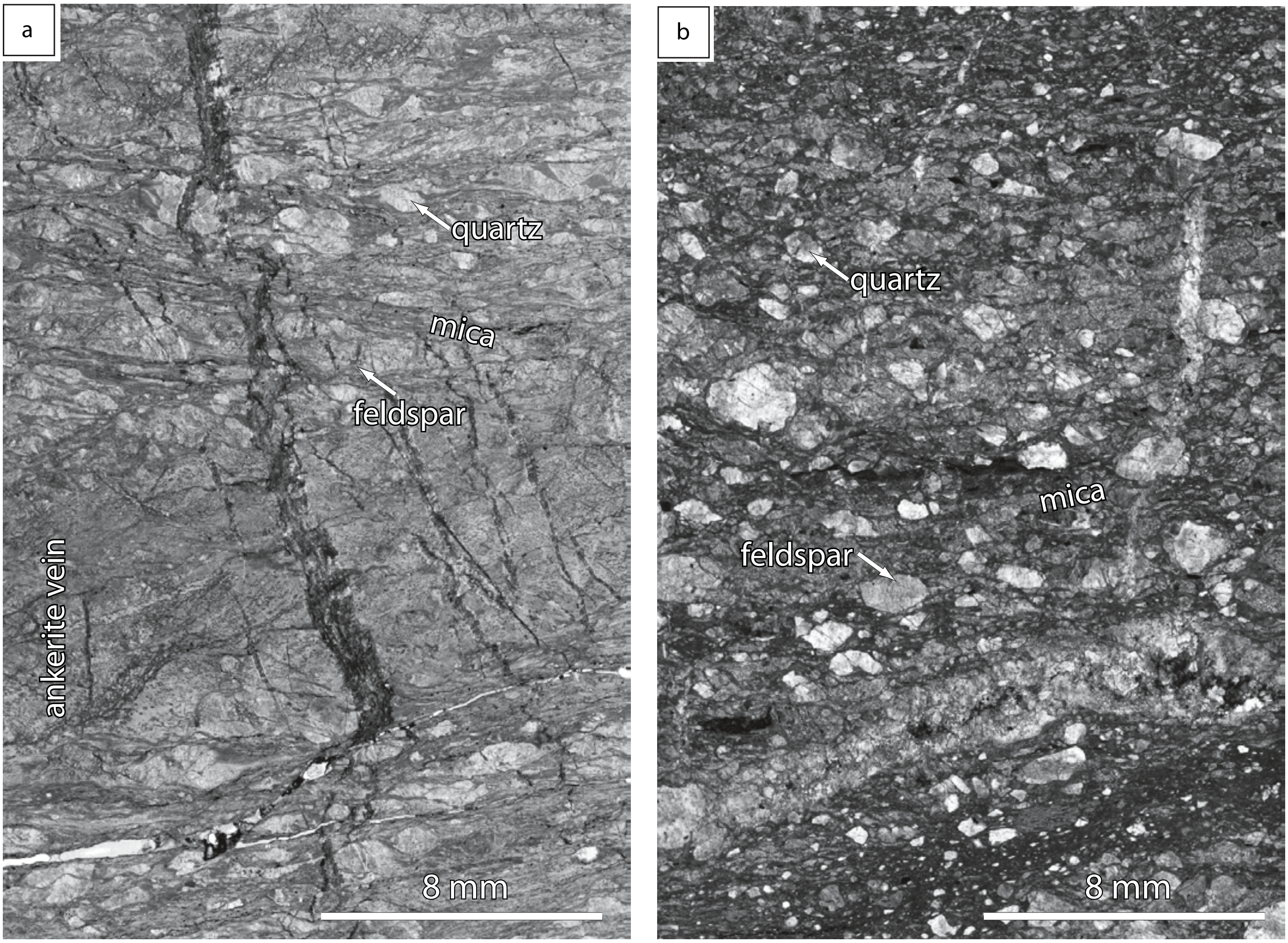

Fig. 11. Thin section photomicrographs taken under plane light from the sampling profile at Pizol; (a) sample GH2 is from 0.15 m above the Verrucano base; quartz and feldspar clasts are elongated parallel to the main foliation, which is believed to be related to thrusting; a large fraction of the sample is comprised of a fine grained mica-rich matrix; several clasts are partially or entirely converted to a fine grained aggregate of quartz and mica and are on the verge of being disintegrated; they show only weak contrast to the matrix; the dark subvertical elongate features are ankerite-rich veins; (b) sample GH7 from 8 m above the Verrucano base; clasts of quartz and feldspar as well as lithic clasts are more clearly distinguished form the fine grained mica rich matrix; the foliation is less pronounced and is ascribed to the Calanda phase of deformation.

and a later low temperature stage of viscous deformation. They also document a strain gradient towards the thrust in the uppermost portion of the footwall limestone. As the finite strain increases gradually toward the thrust, it is difficult to define a clear boundary between the footwall limestone and the calc-tectonite. In the southern section of the thrust, we employ the term Lochseiten calc-tectonite for those portions of the footwall limestone that can be macroscopically identified as a calc mylonite with a millimetre scale lamination (Fig. 5). The calc-tectonite develops a yellow colour and shows progressively increasing signs of cataclastic deformation toward the contact with the Verrucano. It is important to note that at Grauberg the SiO_2, Al_2O_3 and K_2O contents successively increase over the uppermost few decimetres of the footwall limestone and the CaO contents decrease concomitantly (Fig. 8). This may well be explained by a loss of carbonate during deformation and the associated passive enrichment of silicate phases. This view is corroborated by the trend in the calculated modal mineral abundances, as shown in Figure 10. For the Grauberg locality, an increase in the modal abundances of quartz and sheet silicates and a concomitant decrease in the calcite fraction is documented for the uppermost portion of the footwall limestone. The loss of carbonate during mylonitization indicates that dissolution may have been an important mechanism during deformation. Derivation of the calc-tectonite from the footwall limestone is also indicated by the oxygen, carbon and strontium isotope signatures, which show a relatively smooth transition from the unaltered limestone in the footwall to the Verrucano in the hanging wall (Badertscher et al. 2002, Abart et al. 2002) (Fig. 5).

In the central and northern sections of the thrust, the Lochseiten calc-tectonite develops at least in part from progressive deformation of Infrahelvetic carbonate slices. This is particularly well displayed at the eastern face of Foostock in the uppermost Weistannental, where Infrahelvetic slices that are more than 100 m thick and presumably were derived from decapitated Schrattenkalk Formation, grade into the Lochseiten calc-tectonite laterally (Fig. 3). In places, the infrahelvetic slices preserve their primary chemical and isotopic signature and only at their margins become chemically altered during exchange with the surrounding rocks. At Kärpf, the uppermost portion of the calc-tectonite becomes progressively more dolomitized towards the contact to the Verrucano. This is evident form a change in colour in the uppermost portion of the calc-tectonite and from its chemical composition. The MgO content increases from 1 wt.% at 70 cm below the Verrucano to above 8 wt.% at the contact to the Verrucano. Although no spatial variations in the composition of the Lochseiten calc-tectonite can be detected at the Pizol locality, it was most likely chemically altered. From the macroscopic characteristics, the calc-teconite at Pizol was presumably derived from Schrattenkalk Formation. The MgO concentrations are, however, in the range of 7–17 wt.%, which is substantially higher than the typical MgO content of the unaltered Schrattenkalk Formation. Also the ferric/ferrous iron ratios of the calc-tectonite at Pizol do not fall on the transition trend between the relatively reduced flysch in the footwall and the relatively more oxidized Verrucano in the hanging wall (Fig. 9). The fact that the Verrucano in the hanging wall becomes successively more reduced with Fe^{3+}/Fe_{tot} ratios decreasing from about 0.8–0.9 in the unaltered Verrucano to about 0.35 at its base indicates that the Verrucano was infiltrated by a relatively reducing fluid from the footwall. This reduction trend probably represents fluid-rock interaction at a late stage during thrusting, when the Verrucano already rested on flysch. However, the reducing fluid did not penetrate the portion of the calc-tectonite which is present today between the footwall and hangingwall lithologies, as is evident from its comparatively high redox state. This suggests that at Pizol the calc-tectonite was emplaced in its present position at a very late stage during thrusting, when exchange of redox active species between footwall and hangingwall had already occurred. This view is also corroborated by the stable isotope signature of the Lochseiten calc-tectonite at Pizol (Fig. 4). There the $\delta^{18}O$ values are significantly higher in the Lochseiten calc-tectonite than in the carbonates of the underlying flysch and of the Verrucano. These latter two lithologies show a continuous trend of $\delta^{18}O$ values, which is only broken by the extraneous oxygen isotope signature of the Lochseiten calc-tectonite.

Finally stable isotope compositions of the Lochseiten calc-tectonite at the type locality indicate intense reworking by dissolution and reprecipitation of carbonate, so that the primary nature of the carbonate is completely obliterated (Abart et al. 2002; Abart & Ramseyer 2002). In this location, the Lochseiten calc-tectonite may indeed by viewed as a “hydrothermal” mineralization in the sense of Rothpletz (1898).

Conclusions

At its base the Verrucano in the hanging wall of the Glarus thrust is mineralogically and chemically altered. At a relatively early stage sodium was removed from the lowermost Verrucano. This is ascribed to fluid rock interaction associated with thrust-parallel fluid flow in a damage zone immediately above the thrust. Chemical alteration correlates with the breakdown of albite-rich plagioclase and potassium feldspar and the concomitant formation of white mica. The effect of this hydration reaction was presumably to mechanically weaken the Verrucano at its base. At a later stage, chemical interaction between the footwall and hanging wall lithologies produced alteration phenomena that can be locally balanced across the thrust. In the northern section of the thrust, reducing fluids from the flysch in the footwall infiltrated the base of the Verrucano and caused reduction of ferric iron oxides. Upward-directed fluid flow in the northern section of the thrust may have reduced basal friction. Based on the observed trends of bulk rock compositions, three types of Lochseiten calc-tectonite can be distinguished. In the southern section of the thrust, the calc-tectonite developed by progressive deformation associated with a depletion in $CaCO_3$ component of the limestone lithologies in the footwall. In the central and northern sections of the thrust, parts of the calc-tectonite were derived from Mesozoic limestone lithologies that were decapitated from the footwall in the south during thrusting and are now sandwiched as Infrahelvetic slices between the footwall and hanging wall further north. A third type of calc-tectonite is present at the Lochseiten type locality. There the origin of the calc-tectonite can no longer be identified, because of intense reworking by dissolution and re-precipitation during thrust-related deformation. This lead to complete equilibration of the calc-tectonite with the carbonate of the flysch in the footwall of the thrust.

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