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STRUCTURES AND KINEMATICS ALONG THE MORAVIAN - MOLDANUBIAN BOUNDARY PRELIMINARY RESULTS

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Zusammenfassung

Der Ostteil der Böhmischen Masse in Österreich ist charakterisiert durch (1) die Moldanubische Überschiebung und (2) durch die Existenz von großmaßstäblichen Granulitdecken. Strukturuntersuchungen entlang der Plattengrenze von Moravikum zu Moldanubikum machen ein Kollisionsmodell mit schräger Konvergenz wahrscheinlich. Die Deckentransportrichtung wurde als NNO erkannt. Unterschiedliche Strukturassoziationen entlang der Moldanubikums-/Moravikumsgrenze werden auf unterschiedliche Positionen in einer kletternden Deckenbahn zurückgeführt. Dabei wird die Struktur des Messerner Bogens als Rampe mit Schuppencharakteristik gedeutet.

Mylonite entlang der Ränder des Blumauer Granulits sollten Auskunft über die Natur und die Platznahme der Kristallindecken geben. Mikrostrukturen und synkinematisch gesproßte Minerale machen einen sehr raschen Aufstieg des Granulits von Bedingungen der Amphibolitfazies zur unteren Grünschieferfazies wahrscheinlich. Dabei wurde die Gesteinsfestigkeit durch hohen Fluiddruck verringert. Die Richtung der Platznahme ist jedoch bis jetzt noch schlecht abgesichert. Vorläufige Ergebnisse sprechen dafür, daß ein Westtransport in einer späten Deformationsphase beim Granulitaufstieg erfolgte.

Abstract

The eastern Bohemian massif in Austria is characterized by (1) the thrusting of the Moldanubian nappe pile over Moravian foreland series, and (2) the occurrence of large scale crystalline nappes in the Moldanubian zone.

Structural analyses along the Moldanubian/Moravian plate boundary indicate transpressional kinematics with top to the NNE transport of the Moldanubicum. Different strain geometries and structural associations along this plate boundary fit the model of a ductile flat ramp geometry, the map-scale curvature of lithological units, the so called "arc of Messern (Messerner Bogen)" is interpreted as hinterland dipping duplex.

Mylonites along the margins of the Blumau Granulite nappe should give informations about the nature and emplacement history of the crystalline nappes. Microstructures and synkinematic mineral assemblages indicate rapid uplift under retrograde conditions from amphibolite facies to lower greenschist facies. Deformation was achieved by high fluid pressure which reduced the effective rock strength. The displacement direction is poorly proofed. Preliminary results point to top-to-the-W displacement during the late displacement history.

1.INTRODUCTION:

In the western part of the Bohemian Massif in Austria, some aspects of the polyphase history of the Variscan collisional orogeny can be studied in a relatively narrow zone: The Moldanubicum is characterised by the existence of large scale crystalline nappes. (Fuchs und Matura, 1976; Thiele, 1987; Fuchs, 1986 cum lit; Tollmann, 1982). On the other hand, the collision of the Moldanubian nappe pile with the Moravian plate can be studied along the W-dipping Moldanubian thrust. The Moravian zone is characterized by less metamorphosed Cadomian rocks (Bernroider, 1989 cum lit).

Kinematic analyses along a traverse from the Thaya batholith to the Moldanubian granitoids are in progress in order to reconstruct the complex collisional history. Till now, work has been concentrated on two topics:
(1) Structures and motion along the Moldanubian / Moravian plate boundary;
(2) kinematics and emplacement of the Blumau granulite nappe.
Preliminary results on these topics are presented here.

2. GEOLOGICAL AND TECTONIC FRAMEWORK

Intense geological field work during the last decade led to a series of new maps (e.g Thiele, 1987; Fuchs et al., 1984) and a series of partly contradicting concepts about the geology of the Bohemian massif in Austria (Fuchs, 1976, 1986; Matura, 1976; Thiele, 1976, 1984; Tollmann, 1982; Matte et al., 1984). There is a general agreement that the Moldanubian zone is an edifice of multiple deformed and polymetamorphosed nappes. However, the sense of nappe emplacement and the origin of this nappes is the matter of strong discussion. The metamorphic history has been elaborated in some selected areas (e.g. Petrakakis, 1986; Zaydan und Scharbert, 1983; Högelsberger, 1988).

There is by far more agreement in the interpretation of the nature of the Moravian zone which is interpreted as continental crust which is consolidated in Cadomian time (Scharbert und Batik, 1980). The metamorphic history has been recently published by Bernroider (1989, cum lit). Structural investigations along the Moldanubian/Moravian boundary were carried out by Frasl (1968) and Roetzel (1979).

Recently some plate tectonic concepts were evolved which interprete the Bohemian Massif in the frame of the Variscan orogen (Matte, 1986; Franke, 1989).

3. KINEMATICS ALONG THE MOLDANUBIAN / MORAVIAN PLATE BOUNDARY

The geometry of the Moldanubian/Moravian plate boundary in Austria is characterized by a thrust plane which is gently dipping to the West. This structure is complicated by a map-scale arc structure, the so called "Messerner Bogen". The very well exposed footwall rock, the Moravian Bittesch gneiss is a highly defor-

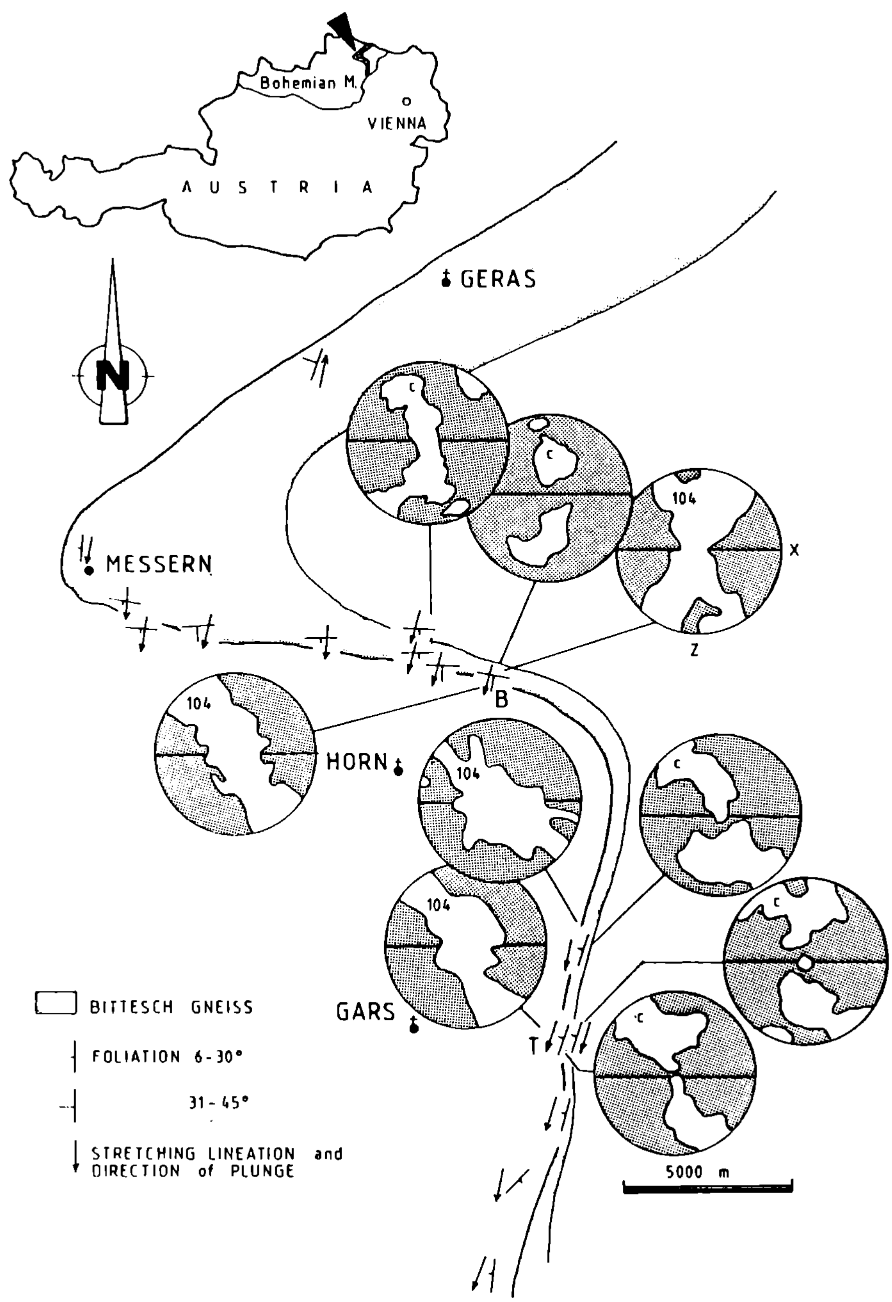

Fig. 1: Sketch of the mylonite zone (Bittesch gneis) along the Moldanubian/Moravian boundary in Austria. Quartz c-axes pattern (c) and pole figures of the (104) planes which are very close to the c-axes, are shown. X defines the orientation of the long axis of the strain ellipsoid (parallel to the stretching direction) and is S-directed. Mention the distinct girdle distribution along the N-S boundary which indicates N-transport and, on the other hand, the cross-girdles along the W-E boundary which is interpreted as flattening component. B and T assign the localities Breiteneich (B) respectively Teichwiesenbach valley (T).

med orthogneiss which is overridden mostly by the "Bunte Serie" of the Moldanubian. Dominant structural elements are a penetrative foliation and an intense stretching lineation as marked by stretched minerals (eg. feldspar), lineation rods and pressure shadows around rigid objects. The whole zone suffered intense deformation, mylonites are the most common rocks. As already mentioned by Frasl (1968), the trace of the foliation follows the curvature of the Messern arc, whereas the stretching lineation is constant in its orientation (Fig.1, 2). Non-coaxial rock flow in the Bittesch gneiss parallel to this stretching lineation with top-to-the-NNE displacement was recognized by Roetzel (1979).

Some outcrops along the Moldanubian/Moravian boundary, mostly in the Bittesch gneiss (footwall) but also some of the hangingwall (Bunte Serie) were examined.

4. METHODS OF KINEMATIC ANALYSIS

Information on the rotational component of strain and the sense of displacement were achieved from S-C fabrics (Berthe et al., 1979); ECC features (Platt and Vissers, 1980); asymmetric strain shadows (eg., Etchecopar and Malavielle, 1987); asymmetric boudins and boudin necks (eg. Hanmer, 1986); orientation of brittle to semibrittle features like tension fissures, hybridic shear veins etc. in brittely deformed minerals and rocks (eg., Harding, 1973); textures of quartz mylonites studied on the U-stage and X-ray goniometer (eg. Schmid and Casey, 1986; Law, 1987).

The methods used to evaluate finite strain respectively the deformational geometry are: Matrix strain was estimated with the method after Fry (1979) and an improved centre to centre technique (Ramsay und Huber, 1983; Unzog, 1989). Semiquantitative evaluation of strain geometry was done by the orientation distribution of quartz c-and <a>-axes and the spatial distribution of extensional structures.

Information on metamorphism and deformation mechanism originate from synkinematic mineral assemblages and the rheological behaviour of rock forming minerals.

5. RESULTS

To illustrate the kinematics along the Moldanubian/Moravian boundary some characteristic outcrops are described. According to the relations of foliation to stretching lineation, the outcrops are diveded into two groups: Those where the stretching lineation is parallel to the dip direction of the foliation (dip-slip characteristics). These relationships are given in the W-E striking Bittesch gneiss north of Horn. Outcrops with strike-slip characteristics where the stretching lineation is parallel to the striking direction of the foliation are found in the N-S running Bittesch gneiss east of Horn and the NE-SW running zone near Messern (Fig. 2).

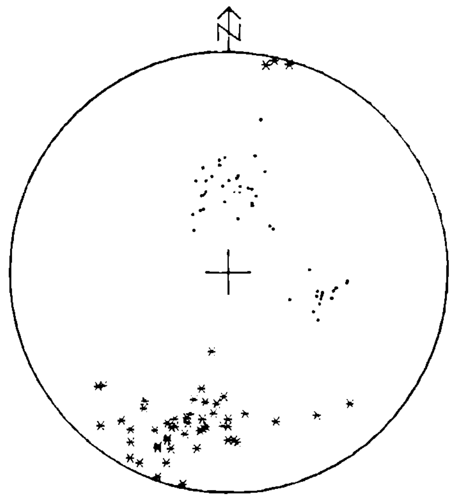

Fig. 2: Orientation data of the Bittesch gneiss along the Moldanubian/Moravian plate boundary. Lower hemisphere equal area plot is used in this and all subsequent diagrams.

6. STRUCTURES IN THE STRIKE-SLIP DOMAINS

One outcrop in the Teichwiesenbachtal ("T" in Fig.1) is described which is representative for the domain east of Horn. Penetrative structures are a West-dipping foliation and a N-S running stretching lineation.

The foliation runs parallel to the thrust surface and shows all characteristics of S-C fabrics. The long axes of elongated feldspar clasts and mica fish are orientated parallel to the S-surfaces, whereas quartz and fine grained mica define the C-pianes. Mica fishes and asymmetric strain shadows are common and indicate the noncoaxial rock flow. In highly sheared zones sets of ECC-planes occur.

Sets of quartz veins developed firstly as extensional veins (Fig. 4) and rotated later towards the shear plane now forming C-parallel veins. Quartz textures were measured in the S-parallel quartz veins (U-stage and X-ray texture goniometer) as well as in the quartzo-feldspatic host rocks. In both types quartz c-axes are distributed in an oblique girdle, the <a>-axes show a well defined maximum slightly oblique to the stretching lineation (Fig. 2, 3). Thus the <a>-direction is ascribed to represent the shear direction.

A schematic block diagram shows the typical features of this zone (Fig. 4).

Matrix strain was roughly estimated by the technique after Fry (1979) and an improved centre-to-centre technique after Unzog (1989). Based on the assumption, that feldspar clasts were primarily uniformly distributed in the igneous source, the final distribution after deformation should reflect the finite matrix strain. In four examples the strain geometry has found to be very close to plane strain (Fig. 10). These results are supported by the existence of a very clear S-C fabric.

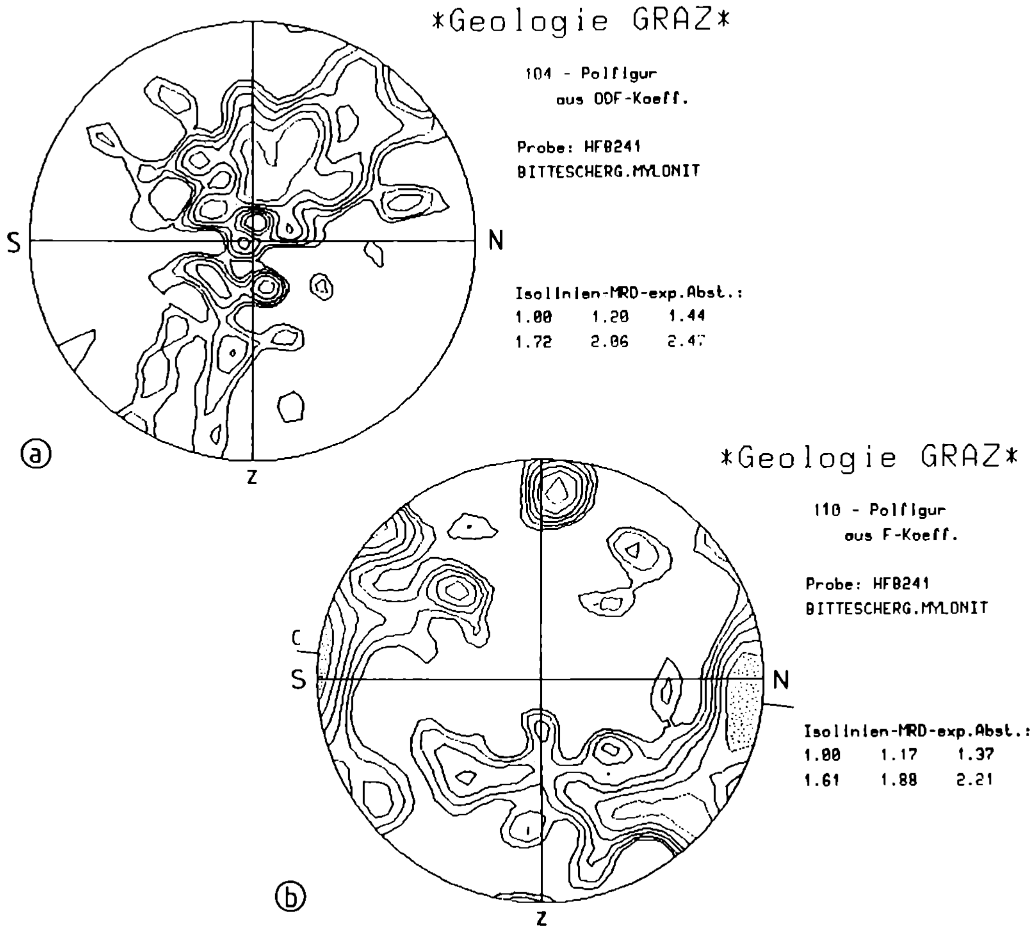

Fig. 3: Pole figures of selected lattice orientations (quartz) as measured with the X-ray goniometer. X-Z sections of the finite strain ellipsoid are shown in this and all subsequent plots. Horizontal line is the trace of the foliation including the direction of stretching (approximately N-S); c is down. a) (104) pole figure indicates N-shearing. b) (110) pole figures, the <a>-axes plot subparallel to the stretching direction and hence is interpreted as glide direction in quartz. C assignes the trace of the shear plane in quartz.

The deformation mechanisms are revealed from the rheology of rock forming minerals. Core-mantle structures in quartz are interpreted as transition from intracrystalline plasticity to dynamic recristallisation (e.g., Langdon, 1985). Some dynamic recrystallizing feldspars (Tullis and Yund, 1987) suggest relatively high temperatures (lower amphibolite facies). Increasing brittle behaviour of minerals and rocks, e.g., extension fissures in feldspar clasts, indicate progressive deformation at decreasing temperatures.
All these structures point to a strike slip shear zone with dextral sense of displacement. (Fig. 11).

Finally, open W-verging flexural slip folds refold these structures. These structures are not interpreted in this paper.

No microstructural investigations were done till now in the strike-slip domain near Messern. Nevertheless there is every reason from macrostructures to assign this zone also as a dextral strike-slip boundary. Boudins of more competent basic dikes which rotated towards the shear plane (Steyrer, pers. comm) are very common in the Taffa valley. Sheared boudins and asymmetric boudin necks (Fig.5) suggest similar kinematics than east of Horn.

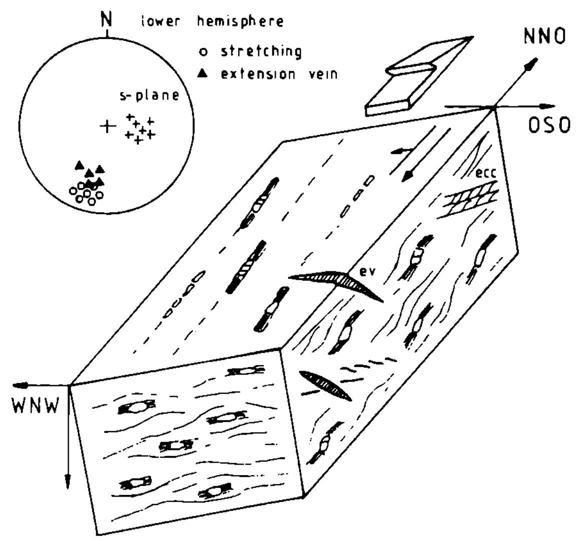

Fig. 4: Sketch of the macrostructures in the Teichwiesenbach valley.
The very clear S-C fabric, asymmetric strain shadows, ecc and extension veins (ev) point to N shearing and a dominant simple shear component.

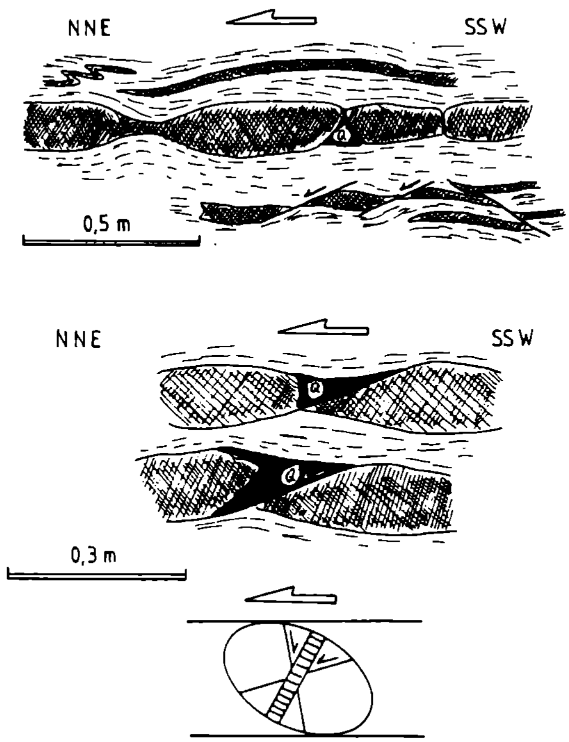

Fig. 5: Two outcrops in the Taffa valley point to NNE transport as indicated by asymmetric boudinage structures and extensional structures. The geometry of boudin fillings of quartz (Q) and shear bands fit a schema as frequently used in brittle tectonics (eg., Harding, 1973).

7. THE DIP-SLIP PLATE BOUNDARY

This boundary is well exposed in some quarries north of Horn. Again one outcrop (north of Breiteneich, in the Stockergraben; assigned "B" in Fig. 2) is described vicarious for this zone.

This outcrop is characterized by the existence of basic and aplitic dikes which rotated towards the shear plane. The heterogeneities in the rock viscosity led to plenty of macroscopic structures. The more competent rocks show boudinage structures with boudin axes in W-E direction (Fig. 6, 9). Asymmetric boudin necks and the spatial distribution of semibrittle structures which are extension fissures, en enchelon arranged veins and extension structures suggest top-to- the-North nappe emplacement (Fig. 7).

In contrast to the strike-slip domain, S-C surfaces occur rather rarely and the shear sense indicated from asymmetric strain shadows around feldspar porphyro-

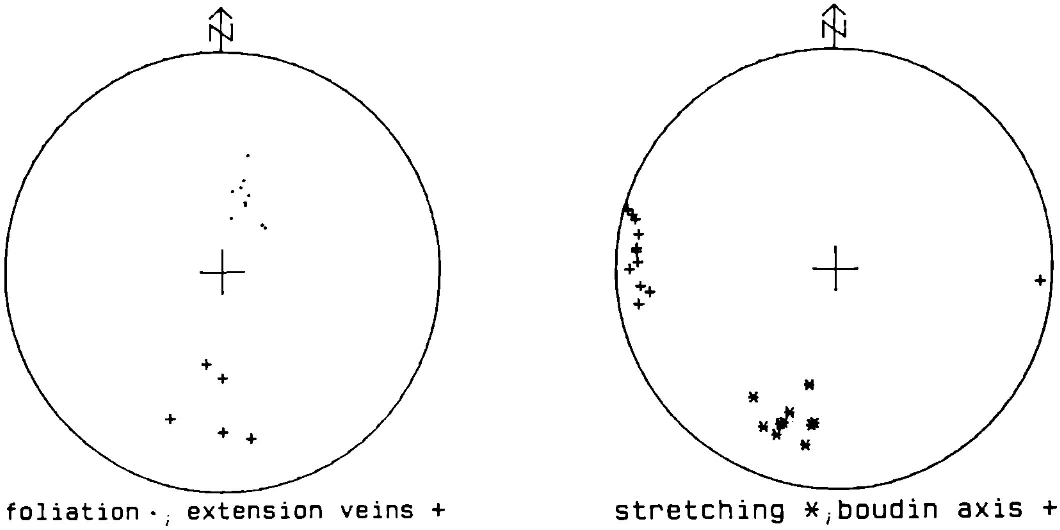

Fig. 6: Orientation data from the quarry near Breiteneich.

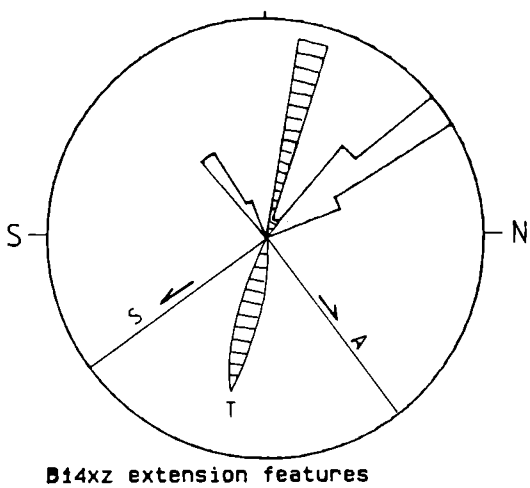

Fig. 7: Schema of the extension features as measured in a thin section (B14XZ, Quarry Breiteneich). These semibrittle structures are thought to represent a late stage of the penetrative deformation. Conjugate sets of shear bands point to a certain amount of flattening strain. The orientation of tension fissures (T), and shear bands (S = synthetic; A = antithetic) even indicate top-to-the S shearing.

clasts are partly contradictionary. This is due to the more coaxial component of strain as revealed from microstructural investigations and textural analyses.

The existence of conjugate sets of shear bands suggests a more coaxial extension in N-S direction. The orientation of extension fissures and shear bands sometimes favour even a top-to-the-South displacement (Fig. 7).

This flattening component of finite strain is also seen in strain analyses (Fig. 10) and quartz textures. Some quartz textures show quartz c-axis with oblique girdle distribution respectively <a>- axes maxima oblique to the stretching lineation (Fig. 2). Displacement from those textures is inferred top to the N.

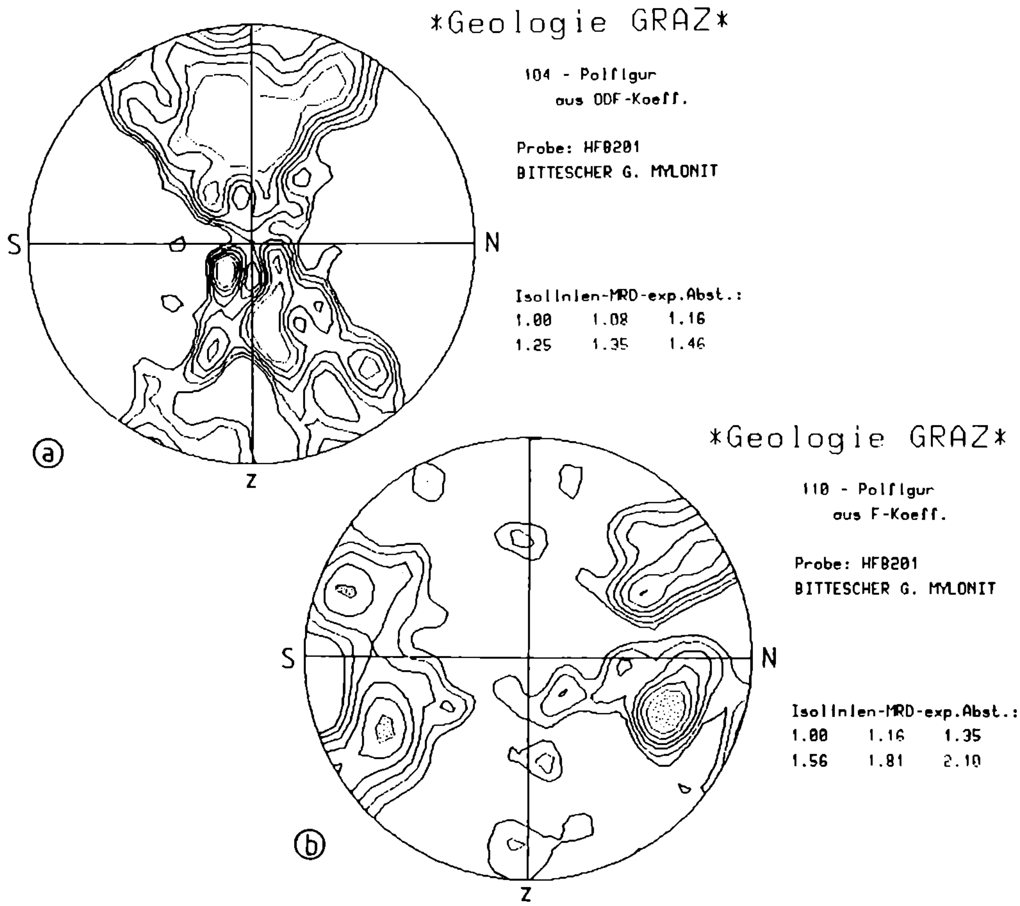

Fig. 8: X-ray examinations at quarry Breiteneich. a) (104) plane poles with cross-girdle distribution indicate flattening strain as well as the a-axes distribution (b) with the four clusters around X.

However, some textures especially those from the quartz veins show very clear flattening features. Quartz c-axes are symmetrically arranged around Z and the <a>-axis form four maxima symmetrically around the X-axis of finite strain (stretching lineation; Fig. 8). These veins originate from extension veins which rotated towards the shear plane. Hence the textures could represent a later strain increment.
In Figure 9 the macroscopic features of the outcrop near Breiteneich are combined in a sketch.

8. DISCUSSION

From these data it is clearly seen that the structures along the Messern arc have different characteristics. The N-S striking margins have dextral strike-slip kinematics with plane strain deformation geometry, the W-E striking border top-to-the-North displacement with flattening strain geometry (Fig. 11).

All these features are easily interpreted as motion over a thrust with a flat-ramp geometry. The dextral strike-slip domains are interpreted as lateral ramps, the situation along the W-E boundary represents the motion over a frontal ramp (Boyer and Elliot 1982). This feature explains as well the flattening strain geometry as the controversial shear senses. Motion over a steepening ramp led first to compression and later on to horizontal stretching when the thrust slice reached the top of the ramp (Fig. 12). Of course, this model of rigid blocks is not a realistic one but the general considerations are transferable for crystalline nappes with ductile deformation (Hatcher and Williams 1986).

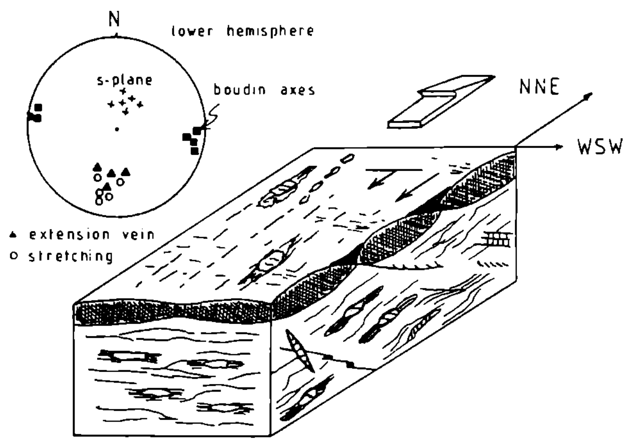

Fig. 9: Sketch of macroscopic features in quarry Breiteneich. There is less amount of impressive shear criteria due to enhanced flattening. Nevertheless extension veins (ev), en enchelon faults, ecc and asymmetrical boudins point to N- displacemen t.

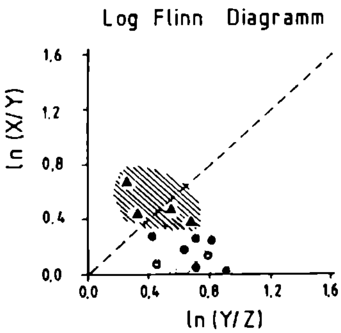

Fig. 10: Matrix strain measurements plotted in a logarithmic FLINN graph. Measurement technique after Fry (1979) and an improved centre-to-centre technique (Unzog, 1989). Triangles represent samples from the N-S striking Bittesch gneiss E of Horn, circles are samples from the W - E striking Bittesch gneiss N of Horn. The orientation distribution of feldspar clasts was used for calculation and the centres of deformed quartz grains (open circles). Not the strain magnitudes are thought to be serious but the strain geometry. There is a clear distinction between flattening strain geometry along the E-W boundary and plane strain geometry along the N-S striking Moldanubian/Moravian plate boundary.

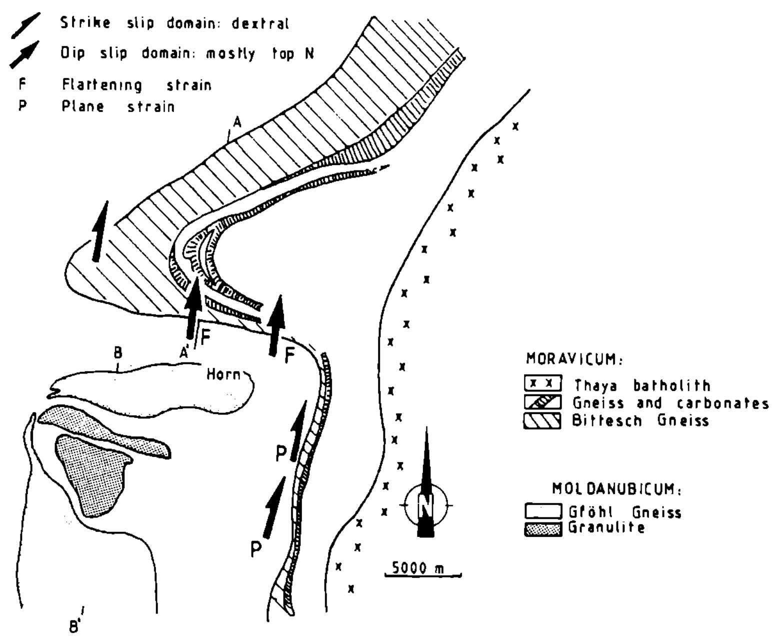

Fig. 11: The structures reflect the kinematics of a transpressional orogen with stacking of the Moldanubian plate in NNE- direction over the Moravian plate. Flattening strain north of Horn is interpreted as an effect of the motion over a ramp (Messern arc, compare also Fig. 12). Repetition of the carbonate series is interpreted as duplex structure. A section is drawn parallel to the stretching direction A- A'and B-B' (Fig. 13).

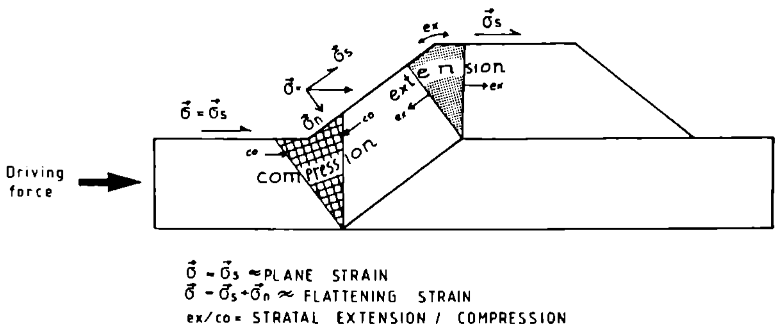

Fig. 12: Schema of the forces which caused the different strain geometries and structures along the Messerner Bogen. Along ramps (dip slip domains) the driving force is splitted in a normal stress component (σn) and a shear stress component (σs). This leads to flattening strain along the ramp. On the other hand, along flats or strike-slip domains the driving force mostly creates shear stress (σs) and hence simple shear (plane strain). This situation causes the different strain geometries documented above. Intrastratal compression respectively extension is expected in the hangingwall due to the transport over the ramp. Compression occurs where the slope steepens at the basal part of the ramp (co), extension (ex) is expected on top of the ramp. Coaxial extension as seen in the semibrittle structures in Breiteneich are explained by this phenomenon.

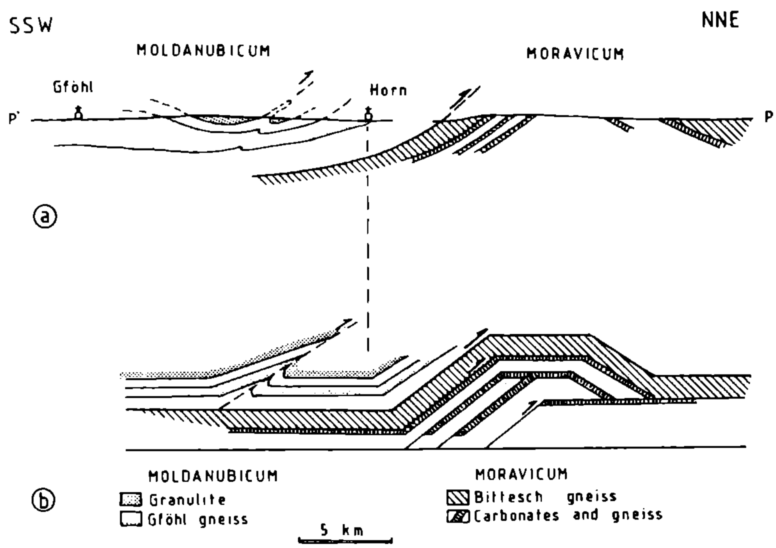

Fig. 13: Preliminary interpretation of the structures along the profile in Fig. 11. The Messerner Bogen is interpreted as duplex structure. Motion over the ramp created a relative depression of the Moldanubian units in the area Horn - St. Leonhard. Structures in the granulite nape of St. Leonhard may also be interpreted with NNE thrusting. For signatures, see Fig. 11.

On a regional scale, the plate boundary is thought to reflect a transpressional orogen with displacement top to the NNE. The lithological units within the Messern arc occur twice or even more times and show increasing thickness towards the frontal ramp. Hence this arc structure of the Messerner Bogen is interpreted as a result of a hinterland-dipping duplex with repetition of the lithostratigraphic sequence (Fig. 13).

In the same way, I would like to explain the situation south of the Messern arc where stacking of the Moldanubian nappes is seen from map scale structures. Motion of the hangingwall rocks over the ramp leads to relative depression of Moldanubian units and partially to imbrication (Fig. 13).

9. KINEMATICS OF THE BLUMAU GRANULITE

The situation within the overriding plate is more complicate. The Moldanubian zone in the eastern Bohemian massif consists of a polyphase metamorphosed (Högelsberger, 1989) and multiple deformed nappe pile. The occurrence of large-scale crystalline nappes in the Variscan orogen is documented by the widespread occurrence of granulite nappes. From the kinematic analysis of these granulites, some information about the nature of these nappes should be achieved. Preliminary results are derived from the Blumau granulite.

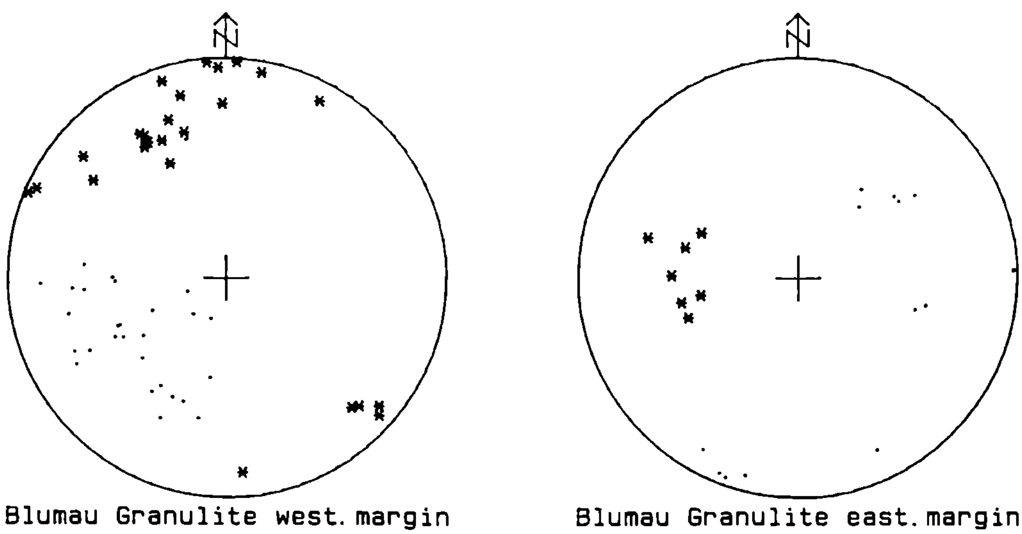

Fig. 14: Orientation data along the W- and E-margins of the Blumau granulite. Points represent the poles of the foliation; asterixes are the stretching lineation. Along the northern margin the foliation dips to the S or SE and the stretching lineation runs NE-SW.

10. TECTONIC FRAMEWORK

The Blumau granulite has the shape of a synform which overlies different tectonic units of the Moldanubian nappe pile (Fig. 14).

Deformation is concentrated along the boundaries of the granulite which form mostly distinct mylonite zones (Thiele, 1987). Thus the kinematics of these mylonite zones should reflect the emplacement history of the Blumau granulite.

Penetrative structural elements within the granulite are a foliation and a stretching lineation. With exception of the western margin of the granulite synform, where the lineation is NW-SE orientated, the stretching lineation runs relative uniformly W-E (Fig. 14, 15).

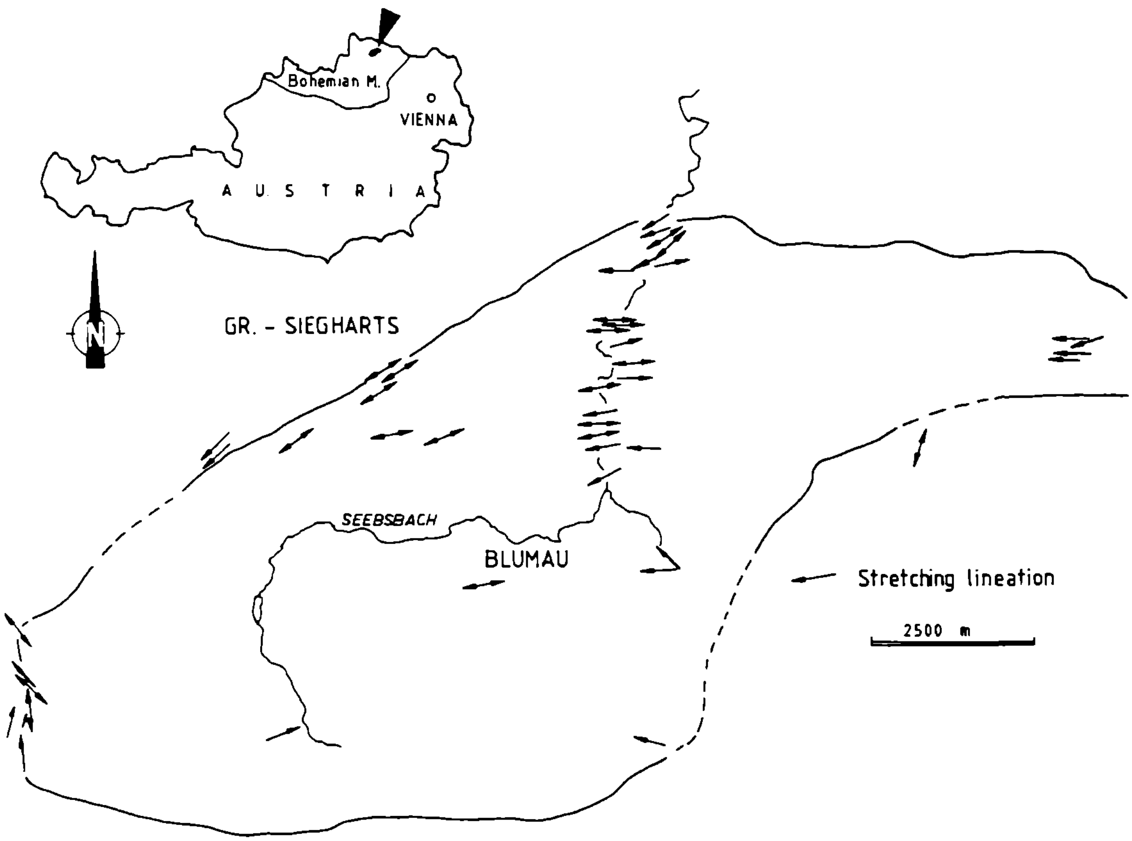

Fig. 15: Regional distribution of stretching directions.

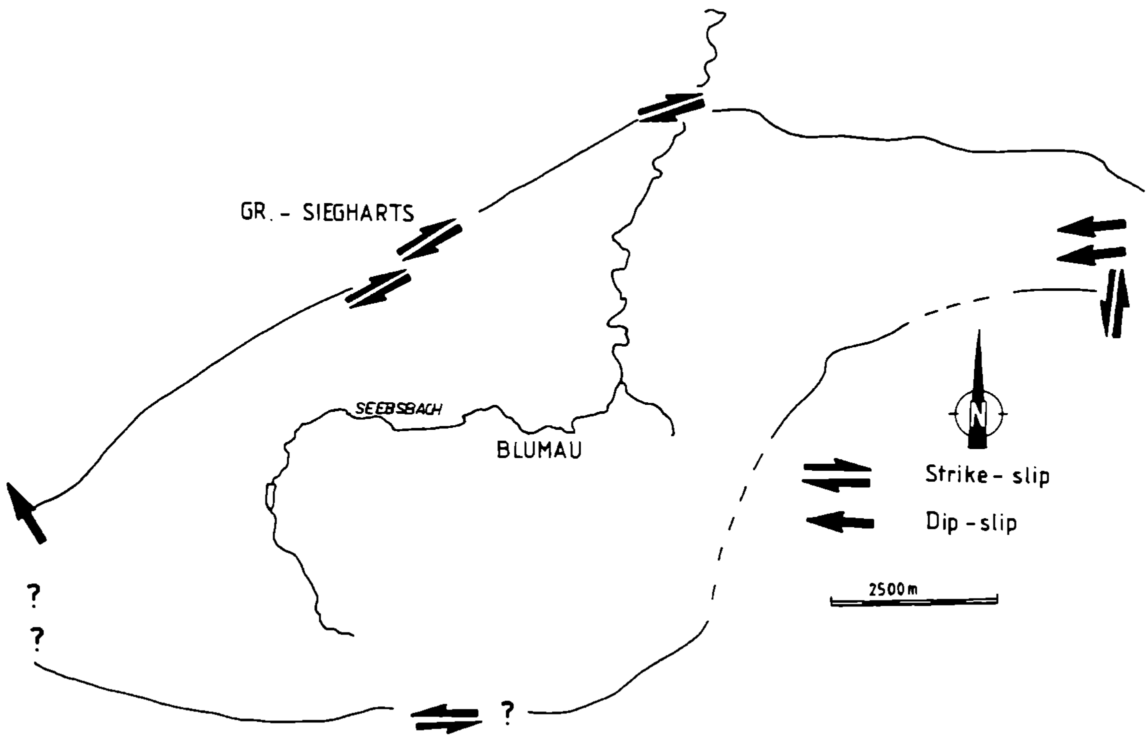

Fig. 16: Sense of shear in the Blumau granulite. For explanation, see text.

11. KINEMATICS AND RHEOLOGY

Other macroscopic structures except the stretching lineation are rare because of the very homogeneous lithology of the granulites. Noncoaxial rock flow and the sense of displacement within the mylonite zones was again inferred from shear sense indicators as mentioned above.

The northern margin of the Blumau granulite is developed as a steeply inclined strike-slip zone with dextral sense of shear. This zone is characterized by the occurrence of very fine grained, mostly high-temperature mylonites as indicated by feldspar recrystallisation.

The southern margin is very poorly exposed. The dominant deformation mechanism along this margin seems to be cataclastic rock flow of feldspar and quartz . No indicators for displacement are found till now.

Along the eastern border of the Blumau granulite the stretching lineation dips to the west (Fig. 14), the few shear sense indicators favour top-to-the-West displacement.

At least the well exposed western margin shows also extremely fine-grained mylonites. The sense of shear is contradictory, maybe there is superposition of two deformational events. Some macroscale structures (vergence of mesofolds) point to top-to-the-NW shearing.

The most amazing fact is the very wide range of deformation mechanisms which accompanied the penetrative deformation. Dynamic recrystallization of feldspar and quartz is realised as well as low temperature plasticity and even cataclastic flow in quartz.

The occurrence of synkinematically extensional fissures which opened under very different temperatures is also very impressive. Whereas along the eastern margin growth of amphibole as vein fillings in amphibolites indicate opening under amphibolite facies conditions, microcracks in quartz at the western margin indicate much lower temperatures. Preliminary investigations of secondary fluid inclusions which form trails parallel to the direction of microcracks suggest very low temperatures. Although some of these hydrous inclusions might have leaked most of these homogenize at about 150 to 200 degrees Centigrade to a vapour phase. These fluids are contrasted by a second type of fluid inclusions which include also CO_2. These fluids are preserved as relicts in quartz grains which are included in garnets and hence were protected from later deformation.

Deviating structures were found in the interior of the granulite synform. Preliminary textural analyses suggest coaxial deformation at very high flattening strain.

12. DISCUSSION

Some more data especially from the southern boundary of the Blumau granulite are needed to prove the preliminary results (Fig. 16). Till now the kinematics of the Blumau granulite is tenderly interpreted in a top-to-the-West displacement under retrograde temperature conditions. The northern margin of the granulite is interpreted as a lateral tear fault with dextral sense of shear. Consequently the southern margin should show sinistral displacement but unfortunately only cataclastic rocks were found till now which show no macroscopic shear sense indicators.

An interesting fact is that this deformation was achieved by a very wide range of deformation mechanisms. Deformation mechanisms, however, are not only influenced by the temperature but also by the stresses and the strain rate (Poirier, 1985; Langdon, 1985). The presence of a reliable amount of fluid reduces the effective stress. This explains the numerous tension fractures which opened under different temperature regimes. The transition of lattice-controlled deformation mechanisms to cataclastic rock flow as found from the southern margin of the granulite is interpreted as accomodation of enlarged strain rates.

The penetrative deformation in the granulites is interpreted as result of rapid uplift of the granulites under retrograde metamorphic conditions from amphibolite facies to at least lower greenschist facies. To explain the change of the fluid regime from CO_2 dominated fluids to aqueous fluids, a source of water-bearing rocks must be found. Stacking of the granulite nappe over the underlying "Bunte Serie" may have caused the dewatering of footwall rocks. Enhanced pore fluid pressure in the hangingwall (granulite) lowered the rock strength and enabled deformation. Thus I conclude that a later part of the thrusting event, the rapid granulite uplift, is represented in these structures.

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