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Symposium
Metamorphism and Deformation

Basel, October 2, 1992

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SWISS SOCIETY OF MINERALOGY UND PETROLOGY

Abstracts of contributions

M.I. Spalla (Milano):

The role of the microstructural control for P-T-path construction in metapelites from the Austroalpine crust (Texel Gruppe, Eastern Alps) (see p. 259–275 this issue).

J. Selverstone (Boulder):

Micro- to macroscale interactions between deformational and metamorphic processes, Tauern Window, Eastern Alps (see p. 229–239 this issue).

M. Thöni (Wien):

Eclogites in the Eastern Alps: their metamorphism and emplacement in the light of new isotopic data (see p. 177–189 this issue).

M. Ballèvre and O. Merle (Rennes):

P-T and kinematical evolution of the Gran Paradiso – Monte Rosa area (Western Alps) (see p. 205–227 this issue).

H. Echtler (Karlsruhe):

Tectonic record of late orogenic high-T/low-P evolution and granitoid emplacement from the Variscan belt

(see also Schweiz. Mineral. Petrogr. Mitt. 73/1, p. 113–128: Variscan crustal evolution in the Vosges Mountains and in the Schwarzwald: Guide to the excursion of the Swiss Geological Society and the Swiss Society of Mineralogy and Petrology)

The internal zones of the European Variscan Belt expose mainly high-grade metamorphic rocks from the middle and lower crust, which were rapidly exhumed during late orogenic stages. Whereas relics of high-pressure rocks result from early stages of convergence and collision (Devonian), the predominant anatectic and migmatitic rocks are related to the main high-T/low-P event during the Carboniferous. Major crustal remobilization is also the origin for several generations and volumetrically important S-type granitoids, which were intruded during this late development of the chain. Granitic magmatism and hT-metamorphism are viewed as the response to crustal stacking. Thickening of the continental crust was accomplished by basement involved thrusting and nappe emplacement during complex collision in the Devonian-Lower Carboniferous period.

The late tectonic evolution of the belt is associated with a characteristic switch from compression to extension related to thermal and gravitational instability. The overall geologic setting and metamorphic core complexes (MCC) in the Massif Central and the Schwarzwald demonstrate the spatial and temporal relationships between metamorphism, magmatism and extension. The main elements of Late Variscan extensional tectonics in association with high-grade metamorphism (hT/lP) are (i) the emplacement of migmatitic domes flanked by (ii) wrench-normal or low-angle normal ductile shear zones which are generally upwarped during progressive uplift and doming of the cores caused by tectonic denudation and unload. Kinematics, sharp thermal and strain gradients, and the subsequent formation of intracontinental sedimentary basins (Stephano-Permian) relate to extension and define asymmetrical MCC as the main geometric feature.

In the Montagne Noire MCC (Southern Massif Central) and Southern Schwarzwald late, retrograde movements control the development of asymmetrical basins. The structural and the metamorphic setting of coarse coal-bearing sequences (Stephanian) deposited upon deeply eroded basement show the influence of outlasting high temperature conditions during basin formation controlled by late displacements superimposed on ductile extensional shear zones.

In both areas the structural setting of granitic rocks and chronological data provide important constraints on the timing of extension in the wide orogenic domain. Synmetamorphic compressive thrusting and wrenching overprinting early granitoids are characteristic for the Lower Carboniferous evolution. Shortly after the cessation of shortening the onset of extension can be defined at about 330–325 Ma in the Schwarzwald; in contrast extension began between 315 and 310 Ma in the southern Montagne Noire. It follows that thrusting and shortening were partly contemporaneous with crustal extension and widespread uplift and erosion in the belt. Similar to processes associated with collision and thickening it appears that extensional tectonics may be associated with a spatial and temporal migration from internal domains (Schwarzwald, Northern Massif Central) towards the external parts of the belt.

Characteristic flat seismic structures (Moho, reflective lower crust) of the post-orogenic continental crust suggest that the observed late orogenic extension allowed a rapid reequilibration and reduction to normal crustal thicknesses within the large orogenic domain. Tectonics and metamorphism in the course of re-adjusting instable overthickened orogenic crust constrain interpretations on crustal rheology and the regional relations between deformation and metamorphism at deeper crustal levels.

V. Trommsdorff (Zürich), **A. Montrasio** (Milano) **and G.B. Piccardo** (Genova):

A model of the structural and metamorphic evolution at the crust-mantle interface during Alpine rifting, Malenco, Italy (see p. 191–203 this issue).

H. Stünitz and S. Schmid (Basel):

Syntectonic recrystallization in calcite, quartz and plagioclase at different metamorphic grades:

The influence of temperature and stress on syntectonic recrystallization mechanisms has been studied by microstructural examination of naturally and experimentally deformed rocks.

Three main recrystallization mechanisms can be identified in different minerals and rocks: 1. Bulge recrystallization, which produces new grains by grain boundary migration of limited range in conjunction with local subgrain or high angle grain boundary formation behind bulges. This mechanism leads to very small recrystallized grains and occurs either at grain boundaries, or in high-strain-zones within grains. Often core-mantle-structures form by this mechanism. 2. Rotation recrystallization, which produces new grains by progressive rotation of subgrains. This mechanism may lead to the formation of core-mantle-structures. 3. Grain boundary migration recrystallization, which represents a rearrangement of grain boundaries by extensive grain boundary migration of long range. Final grain size is often larger than initial grainsize. Mechanisms 1 and 3 are both boundary migration mechanisms, but are distinguished by a "fast" migration rate in mechanism 3 and a "slow" one in mechanism 1. Two or all mechanisms may operate at the same time, but one is usually dominating the microstructure.

Variation of grainsize of syntectonically recrystallized grains formed by mechanisms 1 and 2 is stress controlled. Hence, ideally, grainsize is temperature independent. Experimentally determined flow laws give stress as a function of strain rate and temperature. Since the stress-strain rate relationship is non-linear, grainsize is still primarily dependent on temperature provided the strain rate variation does not exceed more than a couple of orders of magnitude. The dominant recrystallization mechanism, on the other hand, is observed to correlate systematically with metamorphic grade, hence temperature. This could be due to the fact that (1) strain rate variations are relatively small during natural deformation or (2) there is an additional temperature dependence of the recrystallization mechanism at constant stress.

In calcite deformation experiments the transition from mechanism 2 to 3 occurs towards low stresses for constant T or towards low T with a small strain rate dependence. Experimental data in combination with natural deformation suggests that the recrystallization mechanism is clearly stress and temperature dependent. However, the restricted range of possible strain rate variations (10^{-12} to 10^{-14} sec^{-1}) indicates that the change in recrystallization mechanism is primarily temperature controlled.

For naturally deformed quartz, the microstructures show a systematic variation with temperature for most investigated mylonites. At about 200–250 °C extensive bulge recrystallization and development of core-mantle-structures occurs, without major contribution from rotation recrystallization (only at bulges). Rotation recrystallization requiring extensive climb is the dominant recrystallization mechanism at temperatures of the greenschist facies (also developing core-mantle-structures). Grain boundary migration recrystallization becomes the dominant recrystallization mechanism at upper greenschist to amphibolite facies and above.

Plagioclase shows an onset of bulge recrystallization at about the same temperatures as quartz. Compositional changes from intermediate plagioclase towards albite provide additional free energy as a driving force for nucleation and boundary bulging. Rotation recrystallization sets in at temperatures above 450–500 °C, but does not necessarily dominate the microstructures. Bulge recrystallization (and formation of core-mantle-structures) remains important up to granulite facies. In microstructures from the literature no clear cases of boundary migration recrystallization (mechanism 3) have been reported.

Consequently, the different recrystallization mechanisms in these abundant rock forming minerals may be used as a rough guide to temperatures of deformation, especially if they are used in combination. Additional information about stress or strain rate is inherently involved in such an analysis since recrystallisation mechanisms are also stress dependent.

B. Schulz (Erlangen):

Microstructurally controlled geothermobarometry in micaschists: Variscan P-T-deformation paths from the Austroalpine basement (see p. 301–318 this issue).

B. Kamber and M. Engi (Bern):

Tectono-metamorphic interpretation of hornblende-garbenschiefer along the Helvetic-Penninic boundary (see p. 241–257 this issue).

P. Guntli (Zürich):

Die Entwicklung einer transportierten Metamorphose im Kashmir-Himalaja (Kishtwar, NW-Indien).

Development of transported metamorphism in the Kashmir Himalaya (Kishtwar, NW-India).

Das Kristallin des Kashmir-Himalaja gehört tektonisch zum Higher Himalaya. Der Higher Himalaya war ein Teil des indischen Schildes und seiner Bedeckung, welcher während der Kollision des indischen Subkontinentes mit Asien südwestwärts gegen das indische Tiefland überschoben und gehoben wurde. Der Higher Himalaya überfuhr dabei die Einheiten des Lesser Himalaya, im Kashmir aufgeschlossen im tektonischen Fenster von Kishtwar, entlang des Main Central Thrust (MCT). Beide Einheiten zusammen überlagern Molassesedimente, getrennt durch den Main Boundary Thrust (MBT).

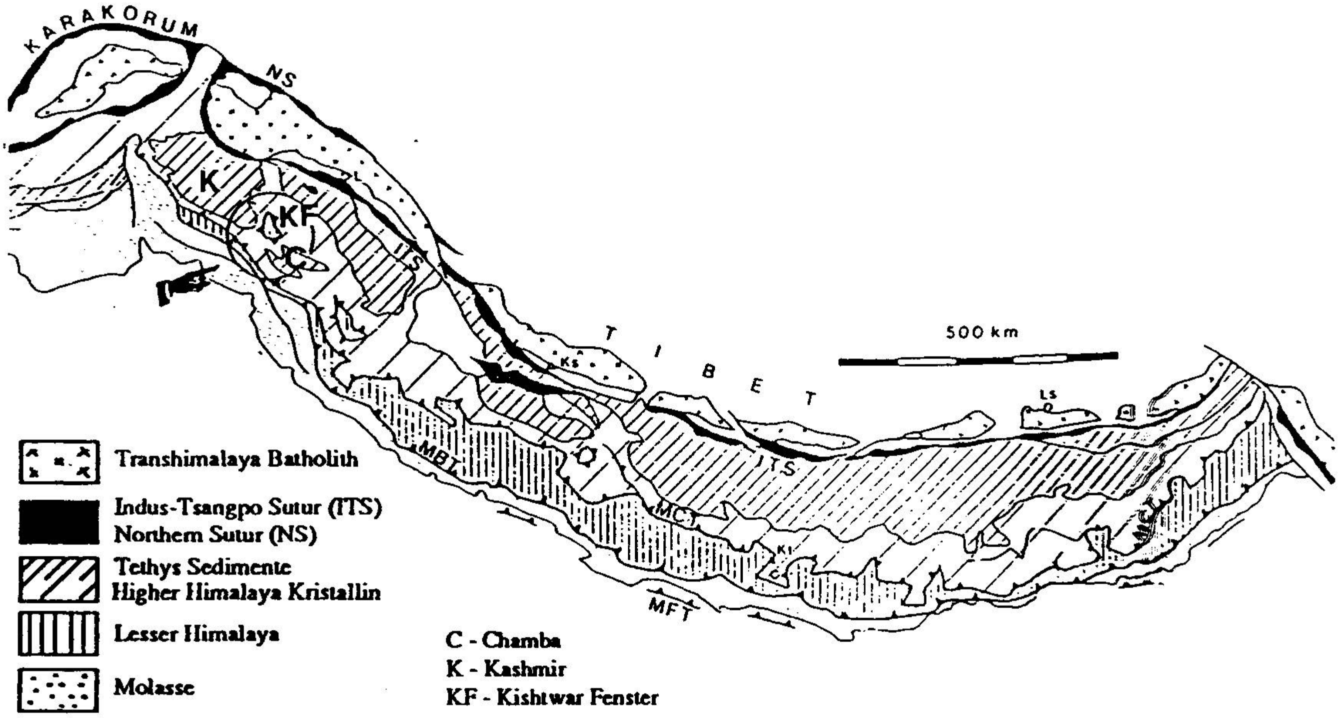
Die untersuchten Einheiten des Higher Himalaya bestehen hauptsächlich aus Metapeliten, seltener Metakarbonaten und -basika, sowie Metagranitoiden. Sie sind metamorphe Äquivalente paläozoischer, sandig-toniger Sedimente, altpaläozoischer Granitintrusionen und des darunterliegenden präkambrischen Schildes. Die polyphase Entwicklung der tertiären Regionalmetamorphose im Higher Himalaya lässt sich mit Hilfe von Mineralparagenesen und Kristallisations-Deformationsbeziehungen in Metapeliten folgendermassen beschreiben:

M1: Granat – Disthen – Quarz – Rutil – Ilmenit ± Staurolith charakterisieren die druckbetonte *M1-Phase* und repräsentieren die prä-MCT-Mineralentwicklung im Higher-Himalaya-Kristallin.

M2: Die M2-Phase ist geprägt durch die Bewegungen am MCT. Nordöstlich des Kishtwar-Fensters führt die SW gerichtete Abscherung am MCT zu starker Hebung und zur Ausbildung synmetamorpher Domstrukturen in den tieferen Teilen des Kristallins. Dabei bilden sich Sillimanit und Kalifeldspat bei teilweiser Anatexis während der temperaturbetonten M2-Phase.

Um das Fenster und südwestlich davon bilden synkinematisch zur MCT-Aktivität gewachsener Fibrolith – Biotit – Staurolith die Mineralparagenese der *M2-Phase.* Sie dokumentiert die Druckverminderung als Resultat der Überschiebung des Higher Himalaya auf den Lesser Himalaya. Die Gesteine des Lesser Himalaya hingegen sind im allgemeinen grünschieferfaziell überprägt. Der Metamorphosegrad im Kishtwar-Fenster steigt zu den tektonisch höheren, stark mylonitisierten Teilen hinan, und es ist eine inverse, prograde Metamorphosezonierung im Lesser Himalaya am Rand des Fensters beobachtbar.

M3: Die fortschreitende, SW gerichtete Kompression führt im Kristallin südwestlich des Fenster zu starker Verfaltung mit SE–NW strei-



chenden Achsen, was mit den Einfaltungen der das Kristallin überlagernden, unmetamorphen Sedimentbecken von Kashmir und Chamba korreliert werden kann.

Syn- und postkinematisch zu dieser gebirgsparallelen Faltung gewachsener Andalusit-Biotit/Chlorit-Quarz ± Staurolith dokumentieren die retrograde *M3-Phase* der post-MCT-Bewegungen. Eine weitere, N–S laufende Struktur hebt das Kristallin zwischen den beiden Becken am Südrand des Fensters und legt die Isograden der M2-Phase weit gegen Südwesten frei. Nach den Überschiebungen am MCT setzten sich die Bewegungen im tieferliegenden MBT fort. Die Lithologien im Bereich des MBT sind geprägt durch Kataklase und Kakiritisierung.

G. Venturini, G. Martinotti and J.C. Hunziker
(Lausanne and Torino):

Cover-basement relationships in the internal part of the Sesia-Lanzo zone.

A field, structural, petrographic and geochemical study of the Eclogitic Micaschist complex located in the lower Aosta and Chiusella Valley has been undertaken to identify the pre-Alpine protoliths and the geodynamic Alpine evolution.

Three main complexes have been defined:

1) the classical polymetamorphic pre-Triassic basement (Eclogitic Micaschist auct.), metamorphosed to amphibolite-granulite grade, intruded by late Hercynian granitoids. and finally re-equilibrated under eo-Alpine HP conditions;

2) an external complex, composed of leucocratic and mesocratic gneisses strongly mylonitized under meso-Alpine greenschist conditions (Gneiss Minuti auct.).

Part of the pre-Triassic basement closer to the external complex has partly reequilibrated under the same metamorphic conditions.

3) a monometamorphic complex, also affected by the same eo-Alpine HP conditions.

This monometamorphic complex can be further subdivided into two subunits:

a) the Bonze unit, composed of sheared metagabbros, metabasites (eclogites, glaucophanites), ultrabasites (pyroxenites) and minor metasediments (micaschists, quartzites and Mn-cherts) and

b) the Scalaro Unit, containing predominantly metasediments (dolomites, calcschists, micaschists, quartzites).

The contacts of the Bonze and Scalaro units with the basement complex are invariably tectonic, and mostly predate the main eclogitic metamorphism.

In the HP unit three main folding phases have been described; a first one associated with the main shear event under prograde blueschist conditions, a second one associated with the eclogitic peak, and a third folding phase associated with minor blueschist reequilibration. A later non pervasive folding event occurred under greenschist conditions. The intensity of this later greenschist event increases with the proximity to the Gneiss Minuti. It is mostly recorded by the Mesozoic sequence of oceanic affinity.

The silicic detrital components in the metasediments suggest that the sedimentary sequence was deposited in an eusialic or near-continental environment. At best on this consideration and on many other field observations it is inferred that this cover sequence is a remnant of an original sedimentary cover of the Sesia Lanzo basement.

A. Lempicka-Münch, M. Cosca, M. Frey, J.C. Hunziker, H. Masson and Ph. Thélin (Lausanne and Basel):

Timing of metamorphism and deformation in the internal Prealps.

The timing of metamorphism and deformation has been studied in several tectonic units of the internal part of the Prealps: two slices of the Prealpes Medianes Rigides nappe (Briançonnais domaine) and some parts of the Zone des Cols (Ultrahelvetic and Infra Niesen), particularly the Lochberg zone (External Penninic domaine). New data on the age and on the mechanism of these events result from:

- detailed mapping combined with structural and stratigraphical analysis;
- mineralogical investigations (index minerals, illite "cristallinity", isotopic analysis, etc.);
- $^{40}Ar/^{39}Ar$ radiometric data.

The radiometric data reveal three main groups of ages:

(a) eo-Alpine (Late Cretaceous – Paleocene) ages record thermal and tectonic events whose importance or even the existence had remained unknown until now in these parts of the Alps;

(b) meso-Alpine ages are related to the internal structuration of the Penninic nappes;

(c) neo-Alpine ages pertain to their transport together with the Helvetic nappes over the external massifs onto their present position.

Combined structural, mineralogical and isotopic studies provide a deeper insight into transport and deformation processes. They reveal significant complications such as several cases of discontinuous inverse metamorphic zonation, thrust related metamorphism and the successive use of distinct thrust surfaces during the movement of nappes or groups of nappes. Thrusts of Cretaceous age have been reactivated during the Tertiary under new dynamical and thermal conditions and with different directions of movement. The role of metamorphic fluids in tectonic and heat transport is stressed.

Th. Baudin, D. Marquer and F. Persoz (Neuchâtel):

Histoire P-T-déformation du socle et de la couverture de la nappe de Tambo: utilisation du géobaromètre phengitique (Alpes centrales suisses) (voir p. 285–299 ce fascicule).

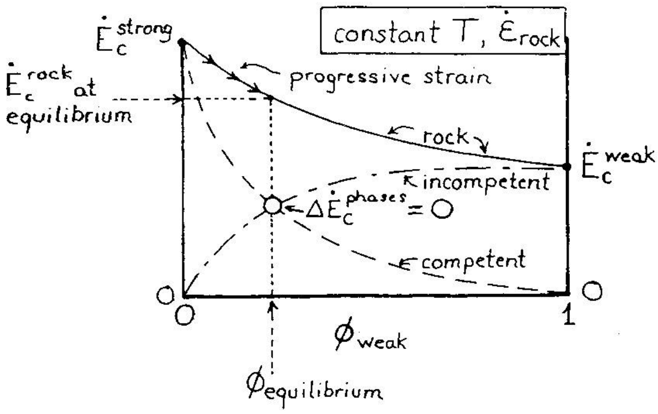
Metamorphism and deformation in the Tambo nappe (Central Swiss Alps): evolution of the phengite substitution during Alpine deformation (see p. 285–299 this issue).

M.R. Handy (Bern):

Heterogeneous shear, strain energy partitioning, and the σ-T-t history of mylonitic fault rocks.

Rock deforms heterogeneously on all scales of observation. After only modest strains, a steady-state (i.e. strain-invariant) foliation develops subparallel to the shearing plane. This foliation comprises interconnected, anastomosing layers of incompetent material that separate layers, boudins, or clasts of more competent material. Similarly, shear zones are incompetent layers that envelop elongate lozenges of less-sheared or unsheared rock. Paradoxically, stress-sensitive microstructures (dynamically recrystallized grain size, subgrain size) in mylonite indicate that the flow stress in interconnected, incompetent layers is higher than in more competent boudins and clasts. On a larger scale, flow stresses in shear zones exceed the flow stress in the adjacent country rock by up to two orders of magnitude. Why are such high stresses concentrated in apparently weak zones of high strain?

This paradox is explained with the following hypothesis of viscous strain energy partitioning: *A heterogeneously deforming rock is at dynamic steady state when the difference in the volume-weighted rates of deformational work (i.e. the delta power dissipation capacity, $\Delta\dot{E}c$ between all the phases is minimized.* The power dissipation capacity, $\dot{E}c$, of a deforming rock is the sum of the power dissipation capacities of its constituent mechanical phases. $\dot{E}c$ is the inner product of the stress tensor, the incremental strain rate tensor, and the volume of deforming material. The breakdown of a loadbearing framework of competent material to form interconnected, incompetent layers (mylonitic foliation or shear zones) is an irreversible structural change that is associated with a reduction of the $\Delta\dot{E}c$ among the phases. It also corresponds to a decrease in the total $\dot{E}c$ of the rock. In rocks with fixed volume proportions, ϕ, of the constituent mechanical phases (e.g. a quartz-feldspar rock), the $\Delta\dot{E}c$ of these phases is



minimized but not eliminated. If, however, the volume proportions of the mechanical phases in the rock can vary (as e.g. in heterogeneously shearing rock), then the $\Delta\dot{E}c$ of the mechanical phases eventually decreases to zero. This involves a growth in the volume proportion of initially weaker material until high stresses and strain rates in narrow shear zones expend the same amount of strain energy per unit time as larger volumes of initially stronger material deforming at lower stresses and strain rates (see figure below).

Mylonitic rocks deform by viscous creep mechanisms (dislocation glide and creep, diffusion/dislocation accommodated grain boundary sliding) so that their $\dot{E}c$ at steady state depends strongly on the temperature and regional strain rate, as well as on the creep parameters and grain size of the constituent phases. Decreasing temperature during uplift of an active shear zone perturbs $\dot{E}c$ equilibrium between the mechanical phases and changes the stable volume proportions of these phases in the deforming rock. This can lead to the preservation of microstructural gradients across shear zones if the rate of stress drop accompanying strain localization adjacent to the active shear zone exceeds the stress sensitivity of the microstructure(s). The application of disequilibrium concepts to microstructural gradients in shear zones is a potential tool for reconstructing the stress history of exhumed sections of the lithosphere.

N. Mancktelow (Zürich):

On Metamorphic "Pressure" during Deformation.

Variation in the state of stress during heterogeneous deformation will be reflected in variation in the effective pressure of metamorphic reaction, whether this is mean stress or the normal stress acting across the reacting interface. It is the potential magnitude of this pressure variation which will determine if it is discernible within the preserved metamorphic mineral assemblages of heterogeneously deformed rocks. The magnitude of the mean stress difference across a non-slipping interface between two materials with viscosity ratio greater than around 20 : 1 is effectively equal to the maximum shear stress for flow in the more viscous material. Progressive shortening of the interface will result in a higher mean stress within the more competent material, whereas extension will result in a lower mean stress. An example where the difference in effective "metamorphic pressure" as the result of deformation may be significant is in the development of low- to moderate-temperature eclogites, which commonly occur as isolated folded layers and boudins within a matrix that does not preserve relics of correspondingly high pressures.

Current experimental data indicate that clinopyroxene- and garnet-rich layers could be very strong for the low geothermal gradients (≤ 10 °C/km) involved in eclogite formation. Effective metamorphic pressure differences between competent layer and weaker matrix of up to 8 kbar (MPa) may be possible. Such high values can be obtained in widely-separated competent layers for values of bulk stress in the overall multilayer which are much lower (by a factor approaching the viscosity ratio). Compression of competent layers results in an initial period of layer parallel shortening and corresponding tectonic "overpressure" equal to the flow strength of the material, followed by an exponential growth of folds and the reduction of this overpressure towards zero in the fold limbs as the rate of deformation (and consequently the flow stress) decreases. As the limbs rotate into the field of incremental extension, the development of an "underpressure" will strongly promote the development of boudins in the competent layer. Overpressure will tend to expel fluids and promote dehydration, underpressure will promote the influx of fluid and retrograde hydration. Within the core of boudins, the deformation rate will be effectively zero: there is thus no pressure differential to assist fluid influx nor continued deformation to accelerate the reaction kinetics and earlier higher pressure assemblages can be preserved.

Regionally heterogeneous deformation could also result in significant regional pressure variation. Extrusion of material between more rigid plates, which has been proposed as a regional mechanism of lateral "continental escape" for both the Alps and the Himalayas, will also be accompanied by a lateral gradient in the effective pressure (otherwise extrusion simply could not occur). Maximum mean stress many times the maximum shear flow stress will develop for deformation zones which are long relative to their width (e.g. around 20 times for a width to thickness ratio of 10). Tectonic overpressure in progressively shortened competent layers, particularly in regions of extrusion between more rigid plates, might help explain the occurrence of isolated layers and pods of eclogite with estimated peak pressures significantly in excess of those in the surrounding matrix.

P. Spillmann (Zürich):

Deformation und Metamorphose im Margna-Bernina-Deckensystem.

Deformation and metamorphism in the Margna-Bernina nappe system.

Im Südabfall des Berninamassivs sind als tiefste tektonische Einheiten mittelpenninische Gneise und deren Sedimentbedeckung sowie ophiolith-haltige, bündnerschieferähnliche Gesteine aufgeschlossen. Darauf überschoben liegen die südpenninischen Ophiolithe, welche ihrerseits von dem unterostalpinen Margna-Bernina-Deckensystem überschoben sind.

Deformation und Metamorphose der Gesteine, die den Deckenstapel im Berninamassiv aufbauen, sind geprägt durch die präalpine geologische Entwicklung der beteiligten tektonischen Elemente sowie durch deren mehrphasige alpintektonische Überprägung. Die variskische Gebirgsbildung führte im unterostalpinen Grundgebirge zu einer inhomogenen Verteilung verschiedener Intrusivgesteine sowie altkristalliner Schiefer und Gneise, welche Verbreitung, Mechanismen und Intensität der alpinen Deformation beeinflussten.

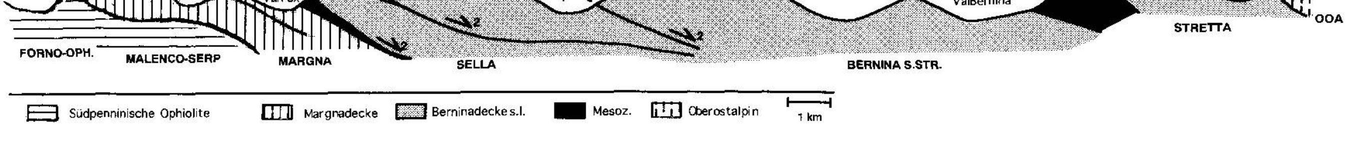
Jurassische Extensionstektonik, gefolgt von der Bildung ozeanischer Kruste und der Etablierung eines passiven Kontinentalrandes, gliederte die am Deckenstapel beteiligten tektonischen Elemente in eine paläogeographische Anordnung, deren Komplexität sich u. a. durch die Verschuppung von ophiolithischen Einheiten mit unterostalpinen Decken äussert.

Die alpine tektonische Überprägung erfolgte mehrphasig. Die eigentliche Deckenstruktur wurde gebildet durch eine eoalpine Überschiebungsphase (E –> W), gefolgt von Abschiebungsbewegungen (W –> E). Die Strukturen dieser Überprägung, welche verbunden ist mit Rekristallisation unter Bedingungen der mittleren bis oberen Grünschieferfazies, zeigen eine bezüglich Lokalisierung und Intensität inhomogene Verteilung der Deformation.

Die Margnadecke als tiefste unterostalpine Decke zeigt eine praktisch vollständige alpine Überprägung des präalpinen Mineralbestandes durch eine penetrative Mylonitisierung und Verschieferung. Eine enorme Streckung ist aus der geometrischen Lage der Margnadecke im Deckenstapel ableitbar.

Die tieferen Teildecken der Berninadecke s.l. (Sella, Corvatsch) sind in ihren altkristallinen Anteilen sowie an den Rändern der Intrusivmassen mylonitisiert und verschiefert, zeigen jedoch auch Bereiche ohne makroskopisch erkennbare Deformation. Die Berninadecke s.str. und die Stretta-Teildecke zeigen lediglich in der Umgebung der mesozoischen Sedimente, welche als Teildeckentrenner funktionieren, eine Mylonitisierung. Die Deformation ist hier auf diskrete Mylonithorizonte beschränkt, während die Hauptmasse der höheren Bernina-Teildecken keine makroskopisch erkennbare Deformation zeigt.

Die kartierbaren Isograde der eoalpinen Metamorphose verlaufen in etwa parallel zu den Deckenkontakten. Das beschriebene Muster der Verteilung und der Intensität der Deformation ist jedoch, abgesehen vom Metamorphosegrad, bedingt durch die lithologische Zusammensetzung und die aktiven Deformationsmechanismen. Während in den Dioriten und Syeniten der westlichen Berninadecke s.str. Deformationsmechanismen, die zu einer Verformungserweichung führten, aktiv waren, verformten sich die granodioritischen und altkristallinen Gesteine der tieferen Decken durch zunehmend verformungshärtende Mechanismen.



Vor der Platznahme der oligocänen Bergeller Intrusion wurde der Deckenstapel durch süd- bis südwestvergente Falten und Überschiebungen überprägt. Die begleitende syn- bis postkinematische Metamorphose ist leicht retrograd bezüglich der eoalpinen Hauptmetamorphose. Weitere Deformationen, welche im Zusammenhang mit Bewegungen an der Insubrischen Linie und mit der Intrusion des Bergells stehen, führten zu einer Verformung des Deckenstapels in eine komplizierte Dom-Becken-Struktur nördlich der Insubrischen Linie und östlich der Bergeller Intrusion.

J. Hermann and O. Müntener (Zürich):

Tektonometamorphe Entwicklung im Grenzbereich Penninikum-Unterostalpin (Malenco, Italien) (siehe Schweiz. Mineral. Petrogr. Mitt. 2/72 p. 225–240).

Tectonometamorphic evolution at the Pennininic-Austroalpine boundary (Malenco, Italy) (see Schweiz. Mineral. Petrogr. Mitt. 2/72 p. 225–240).

Ch. Meyre and A.R. Puschnig (Basel):

Hochdruck-Metamorphose und Deformation im Gebiete Trescolmen (Mittlere Aduladecke, Zentralalpen) (siehe p. 277–283 in diesem Heft).

High-pressure metamorphism and deformation at Trescolmen, Adula nappe, Central Alps (see p. 277–283 this issue).

J. Reinhardt (Bochum):

Textural constraints on timing relationships between metamorphism and deformation. An example from the Mount Isa Block, Australia.

Most commonly, metamorphic rocks preserve only a small part of the pressure-temperature-deformation history they have experienced. However, the P-T-d record may be retrieved to some extent by comparing different rock types from one terrain, using a combined structural-petrological approach. Microscale textures in particular can provide critical information on the timing relationships between successive P-T path segments and corresponding stages of rock deformation. Such timing constraints are crucial for interpreting the P-T history in relation to tectonic and thermal processes that trigger metamorphism.

A detailed examination of amphibolite-grade aluminous schists and cordierite-orthoamphibole rocks from the central Mount Isa Block revealed that these rocks contain a comprehensive record of the P-T path associated with the main folding episode D_2 (REINHARDT, 1992). This deformation is characterized by non-cylindrical, tight upright folds, pervasive axial planar fabrics, and a vertical mineral lineation in S_2.

The inclusion patterns of porphyroblastic minerals document early to late stages in the development of the S2 foliation, from weakly D2-crenulated, but otherwise well-preserved S_1-L_1 fabrics, to a pervasive S_2 with no relics of D_1 structures. This transition is accompanied by a distinct increase in grain size. Accordingly, the porphyroblast generations can be classified as early- to late-D_2, keeping in mind that such a classification can only be valid for a certain position in the metamorphic rock pile (cf. REINHARDT and RUBENACH, 1989).

Apart from purely structural criteria, the growth sequence of the metamorphic minerals is also constrained by reaction textures (e.g. overgrowth, partial replacement) which furthermore allow to identify the underlying metamorphic reactions. With the help of the timing constraints and the reaction relationships in conjunction with a theoretical reaction grid for the pelite model system KFMASH, the reaction history can be reconstructed. The early- to late-D_2 reaction sequence in the aluminous schists involved early cordierite and four generations of Al_2SiO_5 polymorphs (andalusite I–III, sillimanite) which formed from different reactions, at different stages of D_2. Similarly, early- and late-D_2 generations of cordierite can be distinguished in the cordierite-orthoamphibole rocks. The post-D_2 path involves at least two additional Al_2SiO_5 generations (?sillimanite, kyanite, andalusite IV) in retrograde assemblages.

The integration of structural field data and microscopic L-S fabrics with reaction textures demonstrates that prograde, low-pressure/high-temperature metamorphism was entirely synchronous with D_2 crustal shortening. The end of D_2 coincided with the thermal peak of metamorphism. The post-peak metamorphic history shows a period of near-isobaric cooling, before major decompression occurred.

REINHARDT, J. and RUBENACH, M.J. (1989):. Tectonophysics 158, 141–161.
REINHARDT, J. (1992):. Geol. Magazine 129, 41–57.

B. Schulz (Erlangen):

P-T path interpretation from garnets in the Moldanubian diaphthorite zone to the west of

Waldthurn (Bohemian Massif, Northeastern Bavaria).

Sillimanite-biotite-micaschists in the Moldanubian diaphthorite zone at the eastern margin of the Erbendorf-Vohenstrau B-Zone bear strongly zoned garnets. The porphyroblasts are embedded in a metablastic matrix and are surrounded by a foliation with fibrolitic sillimanite. Decreasing, then increasing XMg (from 0.08 to 0.05, then to 0.11) and increasing-decreasing XCa (from 0.017 to 0.128, then to 0.020) from cores to rims of the garnets are considered to reflect continuous reactions within the assemblage Bt-Ms-Pl-Grt-AS-Qtz. The garnets enclosed opaques, quartz, micas and plagioclase during their growth. This allowed to estimate P-T conditions from defined stages of garnet zonation and corresponding biotite and plagioclase by cation-exchange and -net-transfer geothermobarometry.

The recorded evolution started at 550 °C/ 3 kbar, calculated from garnet cores and enclosed biotites (Al^{IV} = 0.83 p.f.u.; Ti 0.25; XMg 0.36) and plagioclase (Ca 0.12; Na 0.91). Ca-rich intermediate garnet zones with enclosed albitic plagioclase (Ca 0.04; Na 0.97) and biotite (Al^{IV} 0.83; Ti 0.34; XMg 0.32–0.34) give evidence of a high-pressure stage at 575–650 °C / 14–18 kbar. Garnet rim with high XMg and low XCa in equilibrium with matrix biotite (Al^{VI} 0.88; Ti 0.34; XMg 0.33) and cores of zoned matrix plagioclase (core: Ca 0.18; Na 0.83/rim: Ca 0.14; Na 0.86) display a HT-LP stage near 700 °C / 3 kbar.

Similar results were obtained from mineral pairs in contact and from pairs in equivalent microstructural positions. A slightly anticlockwise shape of the compressional path signalizes a short-staged disturbance of crustal heat flow during crustal stacking and the nearly isothermal decompressional path suggests rapid tectonic uplift, both in course of a continental collision which affected a crustal regime with high heat flow rates. A late-Variscan age of cooling after the metamorphism is conclusive from K–Ar hornblende data in adjacent metabasites.

B. Kamber, T. Blenkinsop, K. Rollinson, J. Kramers and M. Berger (Bern, Harare/Zimbabwe):

Dating of an important tectono-metamorphic event in the Northern Marginal Zone of the Limpopo Mobile Belt, Zimbabwe: first results.

The Zimbabwe and Kaapvaal Cratons in southern Africa are separated by the ENE–WSW trending Limpopo "Mobile" Belt. This zone of high-grade Archaean rocks, 700 km in length and 250 km wide, can be subdivided into three parallel zones. The marginal zones, predominantly of igneous and meta-igneous character, flank a wider Central Zone (CZ) of mainly meta-supracrustal rocks. The Northern Marginal Zone (NMZ) is separated from the low-grade granitoid-greenstone Zimbabwe Craton by the first occurrence of Opx, significant of 293 ± 60 Ma (Hickman, 1978) old granulite-facies meta-granitoids. According to Coward et al. (1976) this increase in metamorphic T and P is the result of northwards tectonic thrusting of lower continental crust onto the Craton along a set of south-dipping thrust-planes; this is supported by both field observations and geophysical data. Close to the contact in the NMZ late K-rich granitoids form elongate bodies with their long axis parallel to the thrust planes. Some of these granitoids appear syn-tectonic in the field as well as under the microscope and are correlated with the late 2630 ± 15 Ma (1σ error), (Hickman, 1978) K-rich Chilimanzi granites within the Zimbabwe Craton. These intrusions seem to be a possible source for K-rich fluids which retrogressed charno-enderbitic gneisses to granodiorites.

In this work samples of syn-tectonically intruded granites (Tokwe river section), of undeformed late partly charnockitic K-rich granites and of retrogressive granodiorites (i.e. Sarahuru quarry) were dated using the Rb–Sr whole rock technique. The preliminary errorchron (least square regression: MSWD: 7.42) presented in figure 1 is constructed from 18 ^{87}Rb/^{86}Sr, ^{87}Sr/^{86}Sr whole rock measurements. Fitting the data with (McIntyre et al., 1966) model 1 assuming that the amount of scatter is only due to analytical error results in an age of 2593 ± 92 Ma and a ^{87}Sr/^{86}Sr initial of .7045 ± 0.00066. Because the retrogressive granodiorites might retain a strongly over-

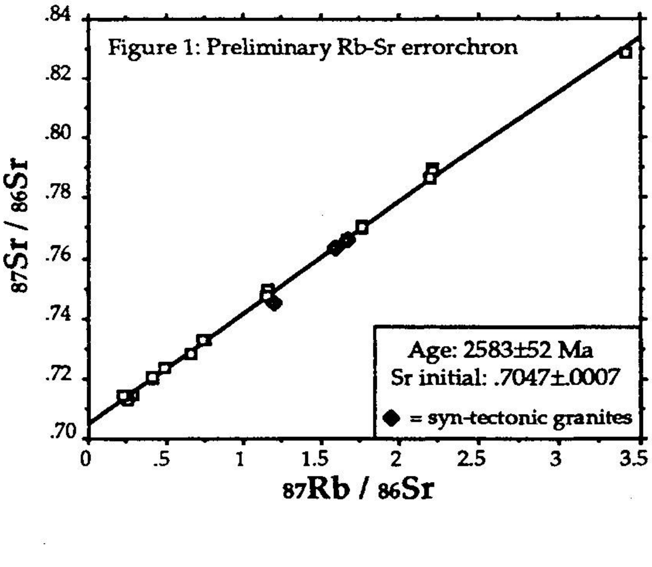


Figure 1: Preliminary Rb-Sr errorchron

printed earlier event we prefer fitting the data with model 3 allowing not only for scatter due to analytical error but also for normally-distributed error in the initial $^{87}Sr/^{86}Sr$. Model 3 age is 2583 ± 52 Ma with an initial of .7047 ± 0.00070. This assumption is supported by the fact that a model 1 fit without the retrogressive granodiorite gives an age of 2573 ± 50 Ma and a Sr initial of .7043 ± 0.00075.

Independent of which model is used we can distill some interesting hints for the tectono-metamorphic history of NMZ from the fact that the three above mentioned rock types can be correlated by an isochron:

1) Given the fact that some K-rich granitoids have intruded syn-tectonically we argue that at least part of the northwards thrusting of NMZ onto the Craton took place around 2550–2600 Ma, which implies a later deformation than that observed in the Southern Marginal Zone (SMZ) and the CZ (> 2650 Ma).

2) There is isotopic evidence for a genetic similarity to the Chilimanzi granite suite as far as the age as well as the high Sr initial ratio are concerned. This supports the idea that the NMZ might represent a portion of lower crust belonging to a thicker portion of the Zimbabwe Craton (Ridley, 1991).

3) Retrogression of chamo-enderbitic gneisses to granodioritic rocks seems to be caused by K-rich fluids related with the late granitoids.

Tectono-metamorphic models for the whole Limpopo "Mobile" Belt often deal with a continent-continent collision scenario. In the light of these new age data one might wonder a) why deformation and plutonism in the NMZ took place significantly later than in CZ and SMZ and b) whether the Zimbabwe Craton was rigid enough to act as counterpart to the Kaapvaal Craton. More data on the P-T-t history of NMZ will be needed to dare an answer to these questions.

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