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Interpreting the Metamorphic Field Gradient of the Koralpe:

Von Kurt STÜWE[1] & Veronika TENCZER[1]

With 4 figures

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Zusammenfassung: Interpretation des metamorphen Feldgradienten in der Koralpe. – Der Eo-Alpine metamorphe Feldgradient in den Ostalpen zeigt einen interessanten räumlichen Zusammenhang: TENCZER & STÜWE (2003) haben gezeigt, dass hochgradig metamorphe Gesteine in der Koralpe eine wesentlich geringere Abweichung von stabilen geothermalen Bedingungen aufweisen (der Metamorphosehöhepunkt lag im Eo-Alpin bei 700 °C und etwa 15 kbar), als die nieder gradigeren Gesteine in der Gleinalpe. Diese Beziehung setzt sich bis in die nördlichen Kalkalpen fort, wo bis zu 300 °C, bei sehr geringern Überlagerungsdrucken dokumentiert wurden. In diesem Artikel diskutieren wir mögliche Gründe für diese Beziehungen. Dazu definieren wir hier eine Reihe von ge- und mis-brauchten Begriffen, die in der Literatur zur Beschreibung von metamorphen Feldgradienten verwendet werden: Der Begriff *metamorpher Feldgradient* ist der horizontale Druck oder Temperaturgradient im Gelände, so wie er im Gelände senkrecht zu den metamorphen Isograden kartiert werden kann. Der Begriff *metamorphe Geotherme* beschreibt die transiente Beziehung zwischen Tiefe und Temperatur in der Erdkruste während der Metamorphose. *Piezothermische* und *Piezobarische Arrays* sind jene Linien, die den Temperatur- bzw. den Druckhöhepunkt der Metamorphose in einem senkrechten Profil durch die Erdkruste über Tiefe und Zeit miteinander verbinden. Die *thermische Perturbations Funktion* beschreibt die Beziehung aus Temperaturhöhepunkt der Metamorphose und seiner Abweichung von stabilen geothermalen Bedingungen. Die *thermische Perturbations Funktion* hat eine positive Neigung wenn hochgradig metamorphe Gesteine weiter von stabilen Bedingungen entfernt sind als niedergradige.

Summary: The Eo-Alpine metamorphic field gradient in the Eastern Alps is characterized by an interesting spatial relationship of rocks of different metamorphic grade: TENCZER & STÜWE (2003) showed that high grade rocks in the Koralpe region (metamorphic peak at 700 °C around 15 kbar) appear to be less thermally perturbed than low grade rocks in the Gleinalpe, or even further north at the base of the nördliche Kalkalpen, where more than 300 °C have been reported at negligible overburden. Possible causes for this interesting relationship are discussed. For our discussion we define (and redefine) a number of used and misused terms related to the description of metamorphic field gradients: The term *metamorphic field gradient* is defined as the pressure or temperature gradient measured normal to metamorphic isograds as mapped in the field. *Metamorphic geotherm* is defined as the transient relationship between depth and temperature in the crust during metamorphism. *Piezothermal* and *piezobaric* arrays are defined as the lines that connect the metamorphic temperature and pressure peaks in a vertical column through depth and time, respectively. The *thermal perturbation function* is defined as the relationship between metamorphic peak temperature and its departure from stable geothermal conditions across a field gradient. The thermal perturbation function has a positive slope when high grade metamorphic rocks are more thermally perturbed than low grade metamorphic rocks and a negative slope when this relationship is reversed.

1. Introduction

The Eo-Alpine metamorphic field gradient in the Koralpe region shows an interesting spatial relationship (TENCZER & STÜWE 2003). The highest grade rocks experienced metamorphism around 700 °C at around 15 kbar kbar (the eclogite facies Plattengneiss shear zone, STÜWE & POWELL 1995, TENCZER & STÜWE 2003). This corresponds to a

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[1] Kurt STÜWE und Veronika TENCZER, Institut für Erdwissenschaften, Heinrichstr. 26, A-8010 Graz, e-mail: kurt.stuewe@uni-graz.at

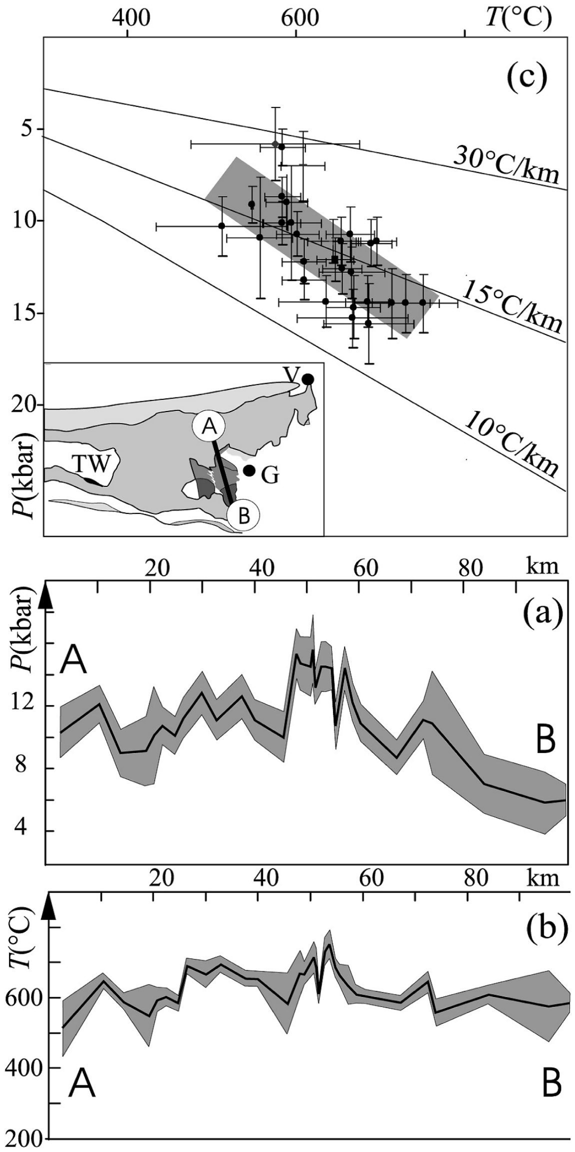

Fig. 1: The metamorphic field gradient in the Kor and Gleinalm region of the Eastern Alps (after Tenczer & Stüwe 2003). (a) shows the peak metamorphic PT conditions of samples from the entire transect plotted in PT space. The slope of this piezothermal array is given by 8°C/km. (b) shows the pressure gradient along the line shown in the inset map in (a) (shaded with increasingly dark colors for increasing Eo-Alpine metamorphic grade; TW = Tauern Window; G = Graz; V = Vienna). (c) shows the temperature gradient (shaded regions around lines are standard deviations). Der metamorphe Feldgradient der Eoalpinen Metamorphose im Bereich der Kor- und Gleinalpe (nach Tenczer & Stüwe 2003). (a) zeigt die metamorphen Peakbedingungen von allen Proben des Profils in einem *PT* Diagramm. Die Steigung des Piezothermalen Arrays ist 8°C/km. (b) Der Druckgradient entlang der Linie die auf der kleinen Karte in (a) gezeigt ist. auf dieser Karte werden dunklere Töne für höheren metamorphen Grad verwendet. TW = Tauern Fenster; G = Graz; V = Wien. (c) Temperaturgradient entlang desselben Profils. Schattierte Bereiche um die Linien sind Standardabweichungen der Daten.

temperature (*T*) depth (*z*) ratio at the metamorphic peak of a mere 12 °C/km (using a conversion from pressure to depth of 1 kbar = 3.7 km) (Fig. 1). Such a gradient is not a significant departure from stable geothermal conditions. In contrast, Eo-Alpine amphibolite facies rocks in the Gleinalm some 30 km further north reached 600 °C around 9 kbar corresponding to a much higher *T/z* ratio around 18 °C/km (TENCZER & STÜWE 2003, FARYAD & HOINKES 2003). A comparison of the two *T/z* ratios indicates a stronger thermal perturbation at shallow levels than at depth and appears to imply heat transfer into shallow crustal levels without perturbing the lower crust. This counter intuitive relationship is repeated in the Ötztal (FRANK & al. 1987) and continues further north into the Grauwackenzone and to the base of the nördliche Kalkalpen where up to 300 °C are reported from rocks that probably experienced negligible overburden during the Eo-Alpine (GAWLICK & al. 1994, 1999; KRALIK & al. 1987). This relationship is in contrast to our intuitive understanding of metamorphism: During regional metamorphism geothermal gradients rise. On the most simple intuitive level this has the effect that the temperatures of rocks at large depths rise more than at shallower levels causing strongly thermally perturbed high grade metamorphism at depth and lower grade, less thermally perturbed metamorphism at shallower levels (black dots on Fig. 2a). In the Koralpe the relationship appears to be that shown by the white dots on Fig. 2a.

In order to describe such relationships we introduce here the term "thermal perturbation function" which basically describes the relationship between metamorphic peak temperatures and their deviation from a stable geotherm along a metamorphic field gradient (Fig. 2b). Interpreting the thermal perturbation function of a given metamorphic field gradient is not trivial. For example, metamorphic field gradients as mapped in the field need not correspond to any one geotherm during metamorphism. This is a particular problem in terrains like the Eastern Alps, where a large number of regional geological studies have emphasized the enormous complications associated with late deformation (e.g. FRISCH & al. 1998, 2000). Metamorphic field gradients may be assembled tectonically by post metamorphic transport of nappes, they may be telescoped, stretched or inverted by syn-metamorphic deformation (GRASEMANN & VANNAY 1999) or they may simply be confused with piezothermal arrays (e.g. OXBURGH & TURCOTTE 1974, RIDLEY 1989, ENGLAND & RICHARDSON 1977, STÜWE 1998a). Evaluating the influence of these processes and, in fact, any interpretation of a given field gradient is hampered by the lack of consensus about the exact meaning of the terms: (i) *metamorphic field gradient*, (ii) *metamorphic geotherm* and (iii) *piezothermal array* (see: TODD & ENGI 1997). We begin therefore with a clear definition of the terminology.

2. Definition of Terminology

The need for a clear definition of terms related to *metamorphic field gradients* was originally realized by P. ENGLAND in the late seventies when it was discovered that metamorphism is diachronous with depth. In the active discussion of this time the new term "piezothermal array" was introduced and the later summary by HARTE & DEMPSTER (1987) summarized some of these term definitions. However, in several studies since, the terms *metamorphic geotherm, field gradient* and *geothermal gradient* have been misused. Some of this confusion stems from the fact that all these parameters (plus several others) have the units of temperature per depth (°C/km), but have very different physical meanings. We therefore redefine these terms here. We propose to use the term *metamorphic field gradient* strictly to describe the change of metamorphic grade with distance (measured normal to the metamorphic isograds), as observed in the field. As such, metamorphic field gradients have the units of dT/dx or dP/dx depending whether the gradient describes the change of temperature or the change of pressure with lateral distance x. However, if

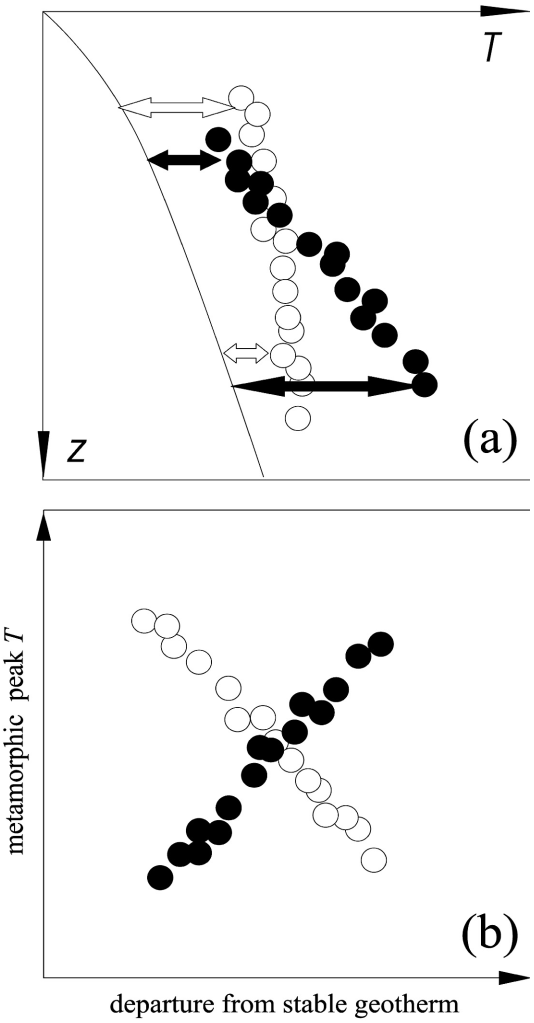

Fig. 2: (a) *Tz* diagram showing two hypothetical data sets collected from metamorphic field gradients (large dots). The black dots indicate a relationship normally expected in regional metamorphic terrains: high grade rocks are more thermally perturbed than low grade rocks. The white dots show the reverse relationship. Rocks of high metamorphic grade are not very perturbed from stable geothermal conditions, while lower grade rocks at shallow levels are substantially thermally perturbed. this is the relationship that is apparently evident in the Eo-Alpine of the eastern Alps. (b) shows these relationships in a diagram where metamorphic peak temperature is plotted against departure from stable geothermal conditions. The two data sets from (a) have qualitatively different slopes defining a positive and a negative thermal perturbation function, respectively.

(a) *Tz* Diagramm von 2 hypothetischen Datensätzen für metamorphe Feldgradienten (große Punkte). Die schwarzen Punkte zeigen eine Beziehung wie sie normalerweise in metamorphen Gebietes erwartet wird: hochgradige Gesteine sind weiter von stabilen Bedingungen entfernt als niedriggradige. Die weißen Punkte zeigen eine umgekehrte Beziehung. Hochgradig metamorphe Gesteine sind nicht sehr weit von Stabilen geothermalen Bedingungen entfernt, wogegen niedriggradige stark thermisch perturbiert sind. Dies ist die Beziehung die scheinbar beim Eo-Alpinen Gradienten in den Ostalpen gegeben ist. (b) Dieselben Beziehungen sind hier in einem Diagramm illustriert wo die abstand von stabilen thermischen Bedingungen gegen die Peak Bedingungen aufgetragen ist. Die 2 Datensätze aus (a) haben in diesem Diagramm qualitativ verschiedenen Steigungen.

the collective data are plotted parametrically in a *T-P* diagram – or in a *T-z* diagram if an appropriate conversion between pressure and depth is performed – then the slope of this data need not document a *metamorphic geotherm* (Sonder & Chamberlain 1992). In contrast, the *T/z* ratio of a single rock will always record one point on a metamorphic geotherm.

The term *metamorphic geotherm* describes the relationship between temperature and depth at a chosen point in time during metamorphism. As such a metamorphic geotherm is a transient feature and contrasts the term *stable geotherm*. In general, metamorphic geotherms change at rates >10 °C/my. During regional (Barrovian-type) metamorphism, metamorphic geotherms will generally be characterized by monotonous increase of *T* with depth, *z* (England & Thompson 1984). However, advectively-heated terrains (contact metamorphism, Buchan-type terrains) or stacked nappe piles may transiently be characterized by metamorphic geotherms in which temperature decreases with increasing depth at some crustal levels (Greenfield & al. 1998, Molnar & England 1990).

The term *piezothermal* (or: *piezothermic*) *array* was clearly defined by Richardson & England (1979) as the line that connects the metamorphic temperature peaks of all rocks in a vertical crustal section through depth and through time (see also: Thompson & England 1984, Ridley 1989). They defined this term in the recognition that exposed crustal sections need not record synchronous metamorphic temperature peaks and that the term "metamorphic geotherm" (which was previously used by England & Richardson (1977) to describe this array) is therefore misleading. Piezothermal arrays are diachronous, and they cross metamorphic geotherms (Fig. 3a). In the field, a piezothermal array is the array of metamorphic peak conditions recorded by an obliquely exposed crustal section. Piezotherms may coincide with metamorphic geotherms for some tectonic settings, for example if exhumation is practically instantaneous.

The *piezobaric array* is the line that connects the metamorphic pressure peak of all rocks in a vertical column through depth and time. As such, the piezobaric array is the baric equivalent to the piezothermal array. This line is usually not recorded directly by the peak parageneses of metamorphic rocks because chemical and textural equilibration of metamorphic rocks is subject to diffusion, which is (according to the Arrhenius relationship) a strong exponential function of temperature but largely independent of pressure. Activation volumes in the Arrhenius relationship are much smaller than activation energies. Thus, even the equilibration rates of pressure sensitive mineral equilibria will be subject to rapid equilibration at high *T* and to a closure temperature as *T* decreases. Nevertheless, the piezobaric array is a useful tool to characterize tectonic processes, for example in terrains where rocks reach their maximum depth at different times (Stüwe & Barr 1998).

2.1 The Thermal Perturbation Function

Unlike the terms discussed above, the *thermal perturbation function* has not been defined in the past and is a new concept introduced here. This function is defined as the relationship between peak metamorphic temperature and the *departure* of peak metamorphic temperatures from stable geothermal conditions. Thus, the thermal perturbation function has a positive slope when high grade metamorphic rocks are more thermally perturbed than low grade metamorphic rocks and a negative slope when this relationship is reversed (Fig. 2). The function may be identified by plotting all data from a metamorphic field gradient on a single *T-z* diagram and measuring the slope of this data relative to the slope of a stable geotherm (Fig. 1a). Positive thermal perturbation functions are characterized by higher- and negative thermal perturbation functions by lower *T-z* ratios than meaningful gradients of metamorphic geotherms.

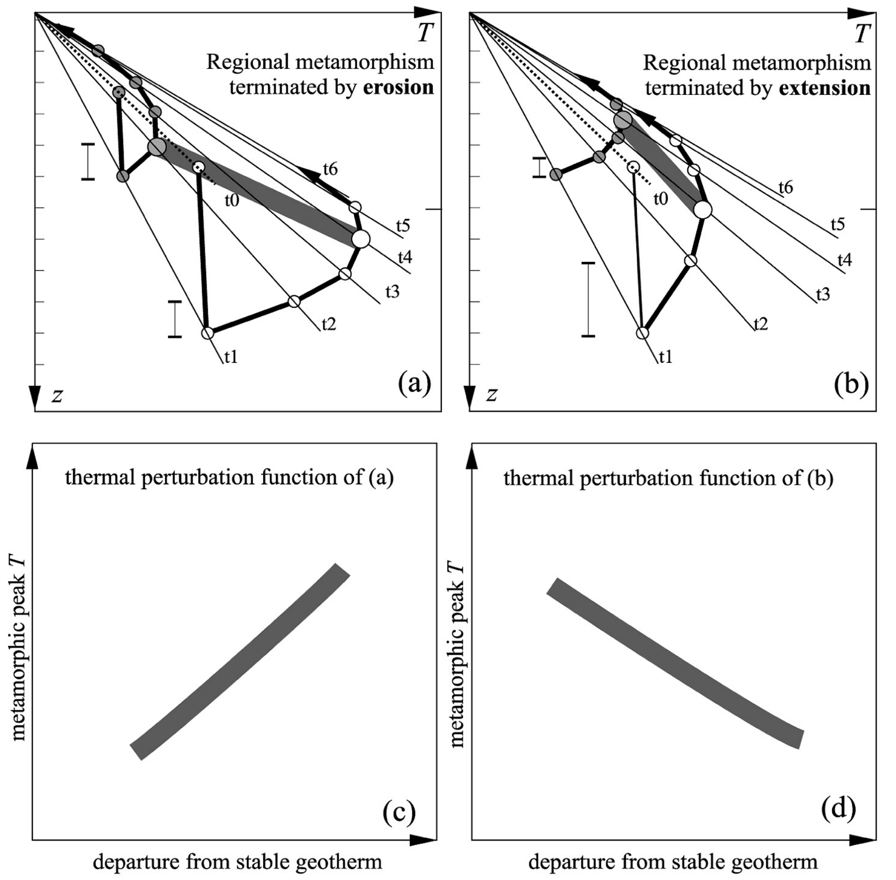

Fig. 3: Cartoons illustrating the thermal evolution of thickened continental crust during (a) exhumation by erosion (all rocks in a vertical column move upwards by the same amount during each time step as indicated by the vertical bars) and (b) exhumation by pure-shear extension (the exhumation rate is depth dependent). Shown are: *Stable geotherms* prior to thickening (dotted lines), *metamorphic geotherms* (thin lines label time from t_1 immediately after thickening to t_6 near the final stages of exhumation), *piezothermal arrays* (shaded bars) and *PTt paths* (thick lines). Note that in (a) the slope of the piezothermal array (the *thermal perturbation function*) has a higher *T/z* gradient than any one geotherm but in (b) it has a lower *T/z* gradient. These relationships are highlighted by plotting the thermal perturbation function in (c) and (d). The scenario sketched in (a) has a positive thermal perturbation function (shown in (c)), while the scenario sketched in (b) has a negative thermal perturbation function. Note also that the timing relationships between high and low grade rocks in (a) and (b) are reversed.

Schematisches Diagramm, das die thermische Entwicklung kontinentaler Kruste in Kollisionsorogenen darstellt. (a) Bei der Exhumation durch Erosion bewegen sich alle Gesteine entlang eines senkrechten Profils mit der gleichen Geschwindigkeit auf die Oberfläche zu. (b) Bei der Exhumation durch Dehnung hängt die Exhumationsrate von der Ausgangstiefe ab. Folgende Linien sind gezeigt: *Stabile Geotherme* vor dem Beginn der Krustenverdickung (gepunktet). *Metamorphe Geothermen* (dünne Linien die mit t_1 bis t_6 beschriftet sind). *Piezothermische Arrays* (schattierte Balken) und *PTt* Pfade (dicke Linien). Beachte, dass die Steigung des Piezothermischen Arrays in (a) steiler, aber in (b) flacher ist als die metamorphen Geothermen. Diese Beziehungen werden noch deutlicher, wenn man die thermische Peturbations Funktion zeichnet die in (c) und (d) für die Beispiele aus (a) und (b) dargestellt ist. Man beachte auch, dass die zeitlichen Beziehungen zwischen hochgradig und niedrig gradigem metamorphen Peak für die 2 Beispiel qualitativ verschieden sind.

3. Interpretation of Metamorphic Field Gradients

It is our aim here to discuss and highlight the interpretation of metamorphic field gradients that have formed due to simple one-dimensional processes. However, in view of the large range of geological processes that may form metamorphic field gradients we feel obliged to summarize other possible causes of metamorphic field gradients. These include: (1) *Superposition of units* of different metamorphic grade postdate to metamorphism. Tectonic processes, for example stacking of nappes with independent evolutions, may juxtapose unrelated units resulting in apparent metamorphic gradients. Metamorphic field gradients produced by such processes usually are discontinuous. (2) *Lateral variation of physical parameters* like thermal conductivity, heat production rate or crustal thickness may cause variations in metamorphic grade (Sonder & Chamberlain 1992). (3) *Synmetamorphic deformation*. Pervasive deformation synchronous to metamorphism may cause telescoping, dilation and even inversion of isograds. Such processes arise usually from complicated, two-dimensional geometries but – if understood – may form valuable tools for the interpretation of both deformation and metamorphism (Grasemann & Vannay 1999). (4) *Variations in equilibration*. Both pressures and temperatures record, in general, the metamorphic temperature peak that rocks have reached. However, because of fluid infiltration, metasomatic processes or other reasons for incomplete equilibration different rocks of may record different stages of their *PT* evolution (Schiffman & Staudigel 1994). This may cause an apparent field gradients in a sequence of constant metamorphic grade.

Aside from these obvious causes for metamorphic field gradients there are a range of somewhat more obscure possibilities, for example pressure gradients due to non-lithostatic stresses (e.g. Stüwe & Sandiford 1994, Petrini & Podladchikov 2000), which we will not consider here. In the following discussion we consider only terrains where none of these causes pertain, so that field gradients may be interpreted in terms of oblique static exposure of laterally continuous sequences.

3.1 Interpreting Field Gradients in Terms of the Thermal Perturbation Function

If a field gradient is indeed an obliquely exposed crustal section, then the relationship between peak metamorphic pressure and temperature is a piezothermal array. Most piezothermal arrays reach higher temperature at larger depths. However, the slope of the piezothermal array relative to a stable geotherm may vary qualitatively defining a positive or a negative thermal perturbation function. The qualitative slope of the thermal perturbation function is characteristic for the underlying thermal processes and provides therefore a useful tool for the interpretation of the tectonic process.

On the most simple level, regional metamorphism terminated by erosion is likely to be characterized by a positive thermal perturbation function, i.e., high grade rocks are more thermally perturbed from stable conditions than their lower grade equivalents (England & Thompson 1984). This may be seen on Fig. 3a where the piezothermal array is shown by the shaded bar. The bar has a positive slope in *Tz* space with rocks at larger depths reaching higher metamorphic temperatures. Interpreted relative to a stable geotherm (dashed line), the piezothermal array also has a positive slope with high grade rocks at large depths having lager departures from stable conditions than lower grade rocks at shallower levels (Fig. 3c). In short, regional metamorphism is likely to be characterized by a positive thermal perturbation function.

In other tectonic environments, this relationship may be reversed so that shallow level rocks are actually more perturbed from stable conditions than deep level rocks. For example, advective heating towards the middle crust (Lux & al. 1986), shear heating in the regions of highest shear strength (Stüwe 1998b), or buried radiogenic heat sources (Sandiford & Hand 1998), are all processes that will cause negative thermal perturbation functions. However, even in purely conductive environments, negative thermal perturbation functions are conceivable. Figure 3b illustrates a simple model for regional metamorphism terminated by pure shear extension. The model is completely analogous to Figure 3a, with the only difference being the exhumation process. It may be seen that the piezothermal array (the line recorded by a metamorphic field gradient) is characterized by a positive slope as in Fig. 3a. However, the relationship relative to a stable geotherm is reversed from Fig. 3a. Lower grade rocks have a larger departure from stable conditions than higher grade rocks, so that the thermal perturbation function has a negative slope (Fig. 3d).

3.2 Time Relationships along Piezothermal Arrays

The fact that timing relationships along piezothermal arrays are a useful tool for the interpretation of thermal processes has long been recognized (denTex 1963, Harrison & Clark 1979, Stüwe 1998a). For example, during contact metamorphism (advectively-heated terrains), rocks nearest the heat source will reach the highest metamorphic grade at the earliest time, while rocks further away from the heat source will reach their peak later and at lower grade. In a grade-time diagram, this relationship has a negative slope (Fig. 4). In contrast, regional metamorphic terrains that are exhumed by *erosion* will be characterized by metamorphic PT paths that reach their temperature peak earlier at shallow crustal levels and low grades and later at deep crustal levels and high grades (England & Thompson 1984). There is a positive correlation between the metamorphic grade and the time of the metamorphic peak.

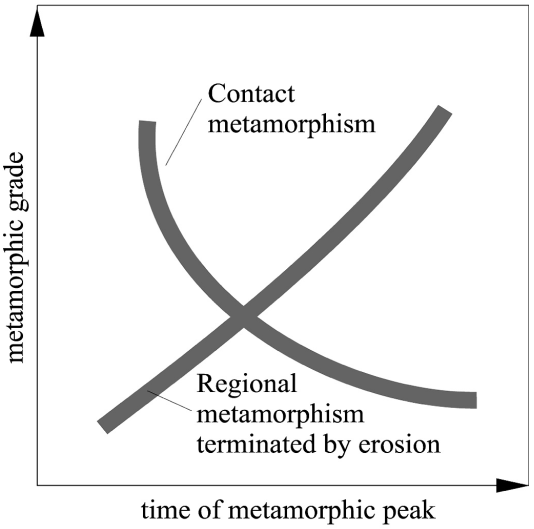

Fig. 4: Cartoon illustrating schematically the timing relationships between peak metamorphic temperature and time of metamorphic peak for contact metamorphism and for regional metamorphism.
Schematische Darstellung die die zeitlichen Beziehungen zwischen Zeitpunkt und Temperatur des metamorphen Höhepunkts für verschiedene metamorphe Prozesse (Kontaktmetamorphose, versus regional Metamorphose) darstellt.

The two models discussed on Figure 3 also have different relationships between peak metamorphic temperature and the time of peak metamorphism. Barrovian type metamorphism in the England & Thompson (1984) model is characterized by higher grade metamorphism at later times and lower grade metamorphism at earlier times. In contrast, metamorphic terrains exhumed by *extension* (as on Fig. 3b) may be characterized by inverted timing relationships, (akin to those of contact metamorphic terrains) because deep level rocks may be forced to cool earlier than shallow level rocks. While natural terrains may not preserve such timing relationships in as elegant and simple manner as the theoretical examples discussed here, we argue that timing relationships between rocks of different metamorphic grade along a continuous field gradient may provide useful information for the interpretation of the underlying thermal processes.

The relationship between *metamorphic grade*, the ti*me of metamorphism* and the *magnitude of the thermal perturbation* may be mapped in the field. Timing relationships between rocks of different metamorphic grade may be dated geochronologically or – in favorable circumstances – by careful field mapping of textural features of mineral growth with respect to time markers across the whole field gradient, for example pervasive deformation events or dike swarms. Nevertheless, only few examples of metamorphic field gradients outside the classic Dalradian sections (Harte & Dempster 1987) have been interpreted in terms of piezothermal arrays and their timing relationships (e.g. Santosh 1985, Nakamura 1994, Scheuvens 2002, Todd & Engi 1997).

4. Application to the Eo-Alpine Field Gradient in the Koralpe

A classic area with a metamorphic field gradient that lends itself to the interpretation in terms of the concepts discussed here is the eclogite type locality in the Koralpe complex, eastern Alps. There, highest grade metamorphic rock are of eclogite facies around 15 kbar and 700 °C and reached these peak conditions around 80 Ma (Tenczer and Stüwe 2003). About 30 km further north, metamorphic pressures decrease to about 9 kbar at 600 °C (Faryad & Hoinkes 2003) indicating a much higher T/z ratio. This relationship continues into the base of the northern Calcareous alps where up to 350 °C have been recorded in rocks with negligible overburden (Gawlick & al. 1994, 1999). The field gradient from south to north appears to be associated with a continues aging of peak metamorphism from 80–90 Ma in the south to about 130 Ma in the Greywacke zone. Thus, lower grade rocks appear to have reached their metamorphic peak earlier than high grade rocks. Regional authors have argued that a comparison between different units is impossible in view of the late tectonic assembly. However, Tenczer & Stüwe (2003) have shown that – at least for the contact between Gleinalm complex and Koralm complex – no sutures have been active during the Eo-Alpine so that an interpretation of the field gradient in terms of a continuous tectonic sequence should be possible.

This timing relationship is consistent with its origin by regional metamorphism. However, in contrast to the relationships predicted by the models for regional metamorphism by England & Thompson (1984), the thermal perturbation function in the Koralpe is negative: The best fit for the collective data of the field gradient indicates a piezotherm with a slope of 8 °C/km which is much lower than meaningful geotherms at the time (Fig. 1). This is inconsistent with an origin by regional metamorphism terminated by erosion. The Koralm example shows that simple tectonic models for the metamorphism of the eclogite type locality may be constrained (or refuted) by metamorphic studies of the field relationships.

Acknowledgements

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Autor(en)/Author(s): Stüwe Kurt, Tenczer Veronika

Artikel/Article: Interpreting the Metamorphic Field Gradient of the Koralpe. 23-33