



# Very low-grade metamorphism in the para-autochthonous sedimentary cover of the Pelvoux massif (Western Alps, France)

Sébastien Potel, Ghislain Trullenque

## ► To cite this version:

Sébastien Potel, Ghislain Trullenque. Very low-grade metamorphism in the para-autochthonous sedimentary cover of the Pelvoux massif (Western Alps, France). *Swiss Journal of Geosciences*, 2012, 105 (2), pp.235-247. 10.1007/s00015-012-0102-8 . hal-03683486

**HAL Id: hal-03683486**

**<https://hal.science/hal-03683486>**

Submitted on 31 May 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

**Very low-grade metamorphism in the para-autochthonous sedimentary cover of the Pelvoux massif (Western Alps, France).**

Sébastien Potel<sup>(1), (2)</sup> & Ghislain Trullenque<sup>(3), (4)</sup>

<sup>(1)</sup> Present address: Institut Polytechnique LaSalle Beauvais - Equipe B2R, 19 rue Pierre Wagnet, BP 30313 – F-60026 BEAUVAIS Cedex.

<sup>(2)</sup> Institut für Geowissenschaften und Lithosphärenforschung, Universität Giessen, Germany.

<sup>(3)</sup> Present address: Institut für Geowissenschaften, Geologie, Universität Freiburg, Albertstr. 23b, Freiburg, Germany.

<sup>(4)</sup> Institute of Geology and Paleontology, University of Basel.

Keywords: Illite crystallinity, very low-grade metamorphism, Western Alps, external crystalline massif.

## Abstract

The metamorphic grade from the para-autochthonous cover of the Pelvoux Massif (PM, western Alps, France) was investigated in Priabonian metamarls, through mineral assemblages, simultaneous measurements of illite and chlorite “crystallinity”, K-white mica *b* cell dimension and K-white mica polytypes content. Kübler (KI) and Árkai (ÁI) indexes display values characteristic for uppermost diagenetic to low anchizonal conditions. These results are supported by the incomplete transformation of K-white mica polytypes from 1M<sub>d</sub> to 2M<sub>1</sub> and are in line with the not annealed status of zircon fission tracks in the southeast zone of the Pelvoux Massif (Seward et al. 1999). Our findings differ from previous results, which suggested epizonal conditions at several places in the northern part of our field area, but are coherent with the temperature estimation suggested by the mineral assemblage described in the literature. These results are further supported by temperature values deduced from fluid inclusion investigations. A small decrease of KI and ÁI values is observed within the basal decollement level of the Priabonian cover, when going from the least deformed zones to the most deformed ones. K-white mica *b* cell dimensions in micas of the area are in the range 9.000-9.040 Å, which corresponds to an inferred geothermal gradient of 25-35°C/Km, similar to the values found further north in the Dauphinois domain (Ceriani et al. 2003). Based on Ferreiro Máhlmann (2001), this can supposed a long stady state heat flow corresponding to a long term metamorphic event like in the eastern Alps.

## 1 Introduction

In the western Alps, the illite “crystallinity” method has been used in order to differentiate the anchizone from diagenesis and epizone domains according to Kübler (1968). The general trend of the metamorphic grade, increasing from W to E, from diagenesis to epizone, is

perturbed by tectonic duplexes and the influence of crystalline basement (Desmons et al. 1999).

In the northern part of the Pelvoux massif, Ceriani et al. (2003) studied the low-grade metamorphism in the region of the Frontal Penninic units (FPU) of the Western Alps between the Arc and Isère Valleys (Fig. 1a-b). The results of the study allowed relating the metamorphism to the different stages of deformation.

Previous metamorphic studies described south of the Pelvoux massif a laumontite-prehnite-pumpellyite subfacies (zeolite facies) in the “grès de Champsaur” formation, with rock-forming laumontite (Aprahmian 1988) and pumpellyite-prehnite in veins (Waibel 1990). On the metamorphic map of the Alps (Frey et al. 1999) and the map of metamorphic structure of the Alps (Oberhänsli et al. 2004) the sub-greenschist facies (epizone) is found in the tiny basement of Fournel and Dormillouse valleys (cf. Fig 1b).

The aim of this contribution is to present the results of a study on metamorphic grade in the southern footwall of the Penninic Basal Contact (PBC, Ceriani et al. 2001), within the Dauphinois cover of the southeastern rim of the Pelvoux Massif, and to compare the results with those from Ceriani et al. (2003). The metamorphic grade was investigated in the globigerina metamarls level and in the Mesozoic cover by mineral assemblages, simultaneous measurements of illite and chlorite “crystallinity” using the KI- and  $\text{AI-}$  methods, K-white mica *b* cell dimension and K-white mica polytypes content. Within the Rocher de l’Yret shear zone (RYSZ, Fig. 1), results are completed by a fluid inclusion study. Quartz precipitates found along the strike slip fault planes dissecting the uppermost basement units from the RYSZ were analysed. All the methods were used for a better P-T estimate to get a higher precision

on the metamorphic evolution in this region and to conclude better with some geodynamic implications. The results of this metamorphic study are compared to those from Ceriani et al. (2003) north of the Pelvoux massif, to the FT data available in the region (Seward et al. 1999; Fügenschuh and Schmid 2003) and previous studies describing mineral assemblage in the “grès de Champsaur” (Aprahamian 1988; Waibel 1990).

## **2 Regional Geology**

The Dauphinois domain is part of the European margin and composed of Variscan basement carrying a thick Permian to Tertiary sedimentary cover. During Mesozoic rifting, the eastern margin of the European plate was substantially thinned. Formation of major tilted crustal blocks allowed for the deposition of thick Mesozoic sedimentary series in asymmetric half grabens intensively described in literature (Tricart et al. 1988; Davies 1982; Gillcrist et al. 1987; Butler 1989; Coward et al. 1991; Huyghe and Mugnier 1995; Lazarre et al. 1996; Sue et al. 1997).

Mesozoic strata are discordantly overlain by a conglomerate formation (Gupta 1997), followed by the classical “Priabonian trilogy” (Ravenne 1987; Apps et al. 2004), which comprises, from base to top: (1) shallow water nummulitic limestone of variable thickness (0 - 50 m), (2) hemipelagic globigerina marls (0 - 50 m), (3) the “grès de Champsaur” formation, a regular alternance of turbiditic sandstones and shales (Perriaux and Uselle 1968; Waibel 1990), whose thickness varies from 700 to 1200 meters. In some areas immediately south of the Pelvoux Massif, the silici-clastic deposits contain up to 50% of volcanic detritus (Debrand-Passard et al. 1984; Bürgisser 1998).

Locally, three Alpine deformation phases ( $D_1$ ,  $D_2$  and  $D_3$ ) can be recognized (Trullenque, 2005).  $D_1$ , first phase of deformation that affected the Dauphinois units corresponds to the third phase of deformation described by Ceriani et al. 2001, i.e Oligocene to lower Miocene

out of sequence thrusting along the Roselend thrust (RT). It is the major deformation phase encountered in the investigated area since it is related to the thrusting along the RT (Ceriani et al. 2001). D<sub>1</sub> deformation structures constantly show WNW-directed kinematic indicators measured directly along tectonic contacts, i.e. consistent with activity along the RT.

The second D<sub>2</sub> deformation phase recorded within the investigated area results in SW-directed movements that overprint the top-WNW D<sub>1</sub> deformation features and which are missing N of the Pelvoux massif. Trullenque (2005) proposed that the D<sub>2</sub> top-SW deformation phase is linked to the formation of the Apeninnes chain, as a consequence of the opening of the Thyrenian basin during Langhian times.

D<sub>3</sub> structures, normal faults related to the Durance fault system (High Durance Faulted Zone, Tricart 2004) are the latest deformation features found in the investigated area. These normal faults are notably responsible for a strong geothermal gradient and seismicity recorded along the Durance valley. The timing of the onset of normal faulting, also recorded north of Pelvoux, remains a matter of debate in literature (see Fügenschuh et al. 1999; Fügenschuh and Schmid 2003; Tricart et al. 2001). However, in this region, fission track data on zircon (Seward et al. 1999) reveal that maximum temperatures were well below greenschist facies conditions. Seward et al. (1999) interpreted the heating event as being due to the emplacement of internal thrust sheets, which thin out westwards.

### **3 Material and methods**

In marine pelites and carbonates, no diagnostic minerals and mineral assemblages form at conditions of very low-grade field. In these rocks, the transitions from non-metamorphic to very low-grade and from very low-grade to low-grade metamorphic domains take place through the diagenetic zone, the anchizone and the epizone, each zone being characterized by specific values of the illite Kübler Index (Árkai et al. 2003). The illite “crystallinity” (IC or

Kübler index (KI; Kübler 1964) is defined as the full width at half maximum of the first illite basal reflection in XRD patterns (Frey 1987; Guggenheim et al. 2002). Guggenheim et al. (2002) recommended that the use of a “crystallinity index” should be avoided, although it may be placed within quotation marks when referring in a limited way to previously referenced work. They also recommended to refer to an index by relating it to the author describing the procedures necessary to define the value, regardless of what the index may actually be describing. Therefore, we will refer for K-white mica to the illite “crystallinity” for raw data and to Kübler index after calibration against Kübler’s scale.

Illite “crystallinity” is considered to be a function of crystallite thickness, the number of lattice defects (Merriman et al. 1990). Temperature is thought to be the main factor controlling the illite “crystallinity”, but other parameters like lithology, time, tectonic stress and fluid/rock ratio may probably have important effect (see Frey 1987). Árkai (1991) and Árkai et al. (1995) proposed a similar index the chlorite “crystallinity” (ChC) or Árkai index (ÁI) to monitor the reaction’s progress.

Twenty-four metamarls samples were collected within the Priabonian and Mesozoic cover formations of the Dauphinois. Sampling was restricted to these formations in order to minimize the petrological effect on the IC. The outcrops density also limited the sampling area, around the Dormillouse and Fournel valleys outcrops are poor. Moreover, westward the Selle Fault cut out the Priabonian formation. The nature, age and tectonic setting of this fault are poorly constrained leading to uncertainties on its effects on the metamorphic pattern. Therefore, samples were taken in the Dormillouse, Fournel, Beassac and Chambran valleys and in the Yret zone (Figs. 1 and 2).

In the different samples, the main schistosity is related to the D<sub>1</sub> phase (Trullenque 2005), the D<sub>2</sub> phase only affects the area south of an E-W line of Beassac valley. The clay fraction analysed is generally related to D<sub>1</sub>.

Samples with detrital mica visible in hand specimen and/or weathered specimens were avoided as far as possible to eliminate detrital contamination. Mineral abbreviations used are from Kretz (1983).

#### *1. X-ray diffraction*

Clay mineral separation was conducted using techniques described by Potel et al. (2006). Carbonate removal was done using a 5% acetic acid ( $C_2H_4O_2$ ) and washed after with deionised water. To minimize the effect of possible detrital clay minerals, we avoided long grinding processes ( $< 15$  sec) and repeated the settling procedure for the  $\leq 2\mu m$  fraction 5 times. Illite and chlorite crystallinity was measured at the University of Giessen on air-dried preparates, using a D501 Bruker-AXS (Siemens) diffractometer,  $CuK\alpha$  radiation at 40 kV & 30 mA and divergence slits of  $0.5^\circ$  with a secondary graphite monochromator. Two slices of each sample were prepared and each measured two times as air-dried and one time glycolated. The range of measurement, the time counting and the step size were as follow: for whole-rock paragenesis between  $2$  and  $70^\circ 2\theta$  with 1 sec and  $0.02^\circ$  step, for air-dried prepare between  $2$  and  $70^\circ 2\theta$  with 2 sec and  $0.01^\circ$  step.

IC was calculated using the software DIFFRACPlus (evaluation/release 2001 by ©Bruker AXS) and MacDiff 4.25 (written by R. Petschick, 17 May 2001). IC measured in Giessen ( $IC_{Giessen}$ ) values were transformed into KI values using a correlation with the SW standards (CIS standards) of Warr and Rice (1994) ( $KI_{CIS} = 1.2702 * IC_{Giessen} - 0.0314$ ) (Table 1). The Kübler index was used to define the limits of anchizone, and the transition values were chosen as follows:  $KI = 0.25^\circ 2\theta$  for the epizone to high anchizone boundary,  $KI = 0.30^\circ 2\theta$  for the high to low anchizone boundary and  $KI = 0.42^\circ 2\theta$  for the low anchizone to diagenetic zone. However, the use of the CIS standards is not universally accepted as giving



Kübler-equivalent zone limits. Kisch et al. (2004) show that the CIS standard values are much broader than those obtained by all other laboratories and that the high- and low-grade boundaries of the anchizone of the raw values of Warr and Rice (1994) are much broader than the Kübler-equivalent. This discrepancy is likely to reflect errors in the conversion of the IC values into Kübler equivalent (Kisch et al. 2004; Ferreiro Mählmann and Frey this volume; Ferreiro Mählmann et al. this volume). Therefore, following the recommendations done by Kisch et al. (2004), we published in the Table 1 the IC<sub>Giessen</sub> and ChC to allow comparison with other laboratories. The same experimental conditions were also used to determine chlorite “crystallinity” on the (002) peak of the second (7 Å) basal reflections of chlorite (Table 1). The ChC measurements were calibrated with those of Warr and Rice (1994) and expressed as the Árkai index (ÁI) (Guggenheim et al. 2002):  $\mathbf{\acute{A}I = 0.8775 * ChC + 0.0239}$ . The anchizone boundaries for the Árkai index were defined by correlation with the Kübler index and are given as 0.24  $\Delta^{\circ}2\Theta$  for the epizone to anchizone boundary and 0.30  $\Delta^{\circ}2\Theta$  for the anchizone to diagenetic zone.

Randomly oriented samples for K-white mica *b* cell dimension and polytype determination of K-white mica were prepared using wood glue on quartz sample holder. The K-white mica *b* cell dimension is based on the  $d_{060,331}$  spacing and on the increasing celadonite substitution that occurs with pressure increase in white mica (Ernst 1963; Guidotti et al. 1989). Guidotti et al. (1989) presented linear regression equations that quantify the changes in the K-white mica *b* cell dimensions of muscovite 2M<sub>1</sub> that result from cation substitutions on the interlayer and octahedral sites. The K-white mica *b* cell dimension value was determined by measurement of the (060) peak of the potassic white mica, if present (Sassi and Scolari 1974), by using the cell-refinement program WIN-METRIC V.3.0.7 (©Bruker AXS).

Illite-muscovite polytype determination was done using a curve of 2M<sub>1</sub>/(2M<sub>1</sub>+1M) peaks ratio calibrated using different mixture of illite polytype following the technique described by

Dalla Torre et al. (1994). Merriman and Peacor (1999) recognized that the wealth of data on variations in white mica polytypism as a function of temperature is generally consistent with predictable trends. However, they recommended that polytype sequences should not be used other than as indicators of reaction progress.

## 2. *Microthermometry*

Quartz-calcite veins were sampled along the Rocher de l'Yret shear zone (RYSZ) (Figs. 1 & 2), in order to substantiate P-T estimation and to reconstruct the fluid evolution history during metamorphism (Frey et al. 1980). Microthermometry investigations were done at the University of Giessen on double polished thin sections and performed using a Linkam THM 600/S/Geo heating-freezing stage coupled to a TMS 94 temperature controller with an error of  $\pm 1^{\circ}\text{C}$ . The stage is mounted on an Olympus microscope with a 100X Objective. The heating and cooling stage was calibrated using synthetic fluid inclusion calibration standard:  $\text{CO}_2$  and  $\text{H}_2\text{O}$  from ©Bubbles Incorporation.

Two-phase (consisting of vapour and liquid at room temperature) fluid inclusions were identified. No dissolved volatile phase was observed, either by melting of  $\text{CO}_2$  at or below its triple point of  $-56.6^{\circ}\text{C}$ , nor by formation or dissolution of clathrate or liquid-vapor equilibrium of a volatile component such as higher hydrocarbons (HHC),  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{N}_2$  or  $\text{H}_2\text{S}$ . Thus, microthermometry was restricted to measuring the melting temperature of ice ( $T_{\text{m}_{\text{ice}}}$ ) and the bulk homogenization temperature of the fluid inclusions ( $T_{\text{h}_i}$ ). As none of the investigated fluid inclusions contained any observable gas component, salinity was derived from the ice melting temperature in NaCl-equivalence after Hall et al. (1988). Density for fluid inclusions with homogenisation temperatures less than  $200^{\circ}\text{C}$  are from the equations of state given by Brown and Lamb (1989) and for temperatures greater than  $200^{\circ}\text{C}$  are from

Zhang and Frantz (1987). The isochores were calculated from the equation of state given by Zhang and Frantz (1987).

### 3. Raman microspectrometry

Gas, liquid and solid phases were investigated at the University of Frankfurt am Main using a Raman microprobe Leica/Renishaw and the software Renishaw WiRE™ 2.0 and GRAMS. An Argon laser (green laser:  $\lambda = 514.5 \text{ nm}^{-1}$ ) was used as excitation laser radiation. The Raman microspectrometry was used to identify the presence of CH<sub>4</sub>, CO<sub>2</sub>, HHC (C<sub>2</sub>H<sub>6</sub> or C<sub>3</sub>H<sub>8</sub>) and N<sub>2</sub> in fluid inclusions. The relevant peak is positioned at 2917cm<sup>-1</sup> for CH<sub>4</sub>, 1285 and 1388 cm<sup>-1</sup> for CO<sub>2</sub>, 2890 and 2954cm<sup>-1</sup> for C<sub>2</sub>H<sub>6</sub> or C<sub>3</sub>H<sub>8</sub> respectively and 2331cm<sup>-1</sup> for N<sub>2</sub> (Burke 2001). The small size of most fluid inclusions (< 10µm) and the large vertical dimension of the laser beam focus (4µm in diameter) cause the presence of Raman lines of the enclosing quartz (1160cm<sup>-1</sup>) in the spectra of fluids. This line does not interfere at all with the CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub> lines.

## 4 Results

### 1. Mineralogy

The mineralogy of the studied samples is given in Table 1.

In the Priabonian and Mesozoic meta-marls, the mineral assemblages consist of quartz + K-white micas + chlorite and calcite with minor amounts of albite. Gypsum is detected in some samples from the Fournel and Dormillouse valleys (Do2, Fo3a and Fo3c). In the fraction <2 µm, illite-muscovite predominates, chlorite and quartz are significant, and feldspar, if detected, is only present in small quantities.

## 2. *Characteristics of the phyllosilicates*

Figure 2 shows the distribution of the KI data, the values of which are listed in Table 1.

The values in the Dormillouse valley vary between uppermost diagenetic conditions ( $0.43\Delta^{\circ}2\Theta$ ) in the south and low anchizonal values ( $0.36\Delta^{\circ}2\Theta$ ) in the north. In the Fournel, Beassac and Chambran Valleys, the KI data indicate low anchizonal conditions (0.35 to  $0.41\Delta^{\circ}2\Theta$ ). In the Yret Zone, illite crystallinity values correspond to the diagenesis/anchizone boundary ( $0.37$  to  $0.43\Delta^{\circ}2\Theta$ ) (Fig. 2). No trend can be observed between KI and elevation of the sample. However, a trend can be observed in each valley or zone, with an increase from south to north of KI values. This is similar to that Aprahamian (1988) described.

Figure 2 presents the distribution of  $\acute{A}I$  values in the studied area. The pattern of very low-grade metamorphism shown by  $\acute{A}I$  agrees well with the pattern of the KI (Fig. 2). A positive linear correlation ( $R^2 = 0.64$ ) is found between KI and  $\acute{A}I$  values (Fig. 3a). This gives confidence on the fact that illite and chlorite “crystallinities” actually refer to the same P-T conditions and thus the same experienced T-t history.

The percentage of  $2M_1$  illite-muscovite polytype relative to the KI in the studied area shows a positive trend with increasing metamorphic grade (Fig. 3b).

Sassi and Scolari (1974) determined a semi quantitative relationship between the K-white mica  $b$  cell dimension and the metamorphic pressure gradient under greenschist facies condition. They plotted the K-white mica  $b$ -values as cumulative frequency curves in order to compare them with other metamorphic belts. Guidotti and Sassi (1986) collated published K-white mica  $b$  cell dimension data for greenschist and blueschist facies rocks. They presented a qualitative plot of  $b$  cell dimension as a family of curves in P-T space. The values presented by Guidotti and Sassi (1986) do not extend to the sub-greenschist facies. However, the considerable amount of K-white mica  $b$  cell dimension data from very low-grade metapelites

accumulated in different metamorphic belt corroborate the groupings found by Guidotti and Sassi (1986), as shown by Merriman and Peacor (1999). K-white mica *b* cell dimensions were calculated for 21 samples from the anchizone (three samples were not integrated due to interferences and poor intensity signal), all fall in the same range with a minimum 8.998 and a maximum 9.028 Å values (Table 1). Specimens from the Mesozoic cover have lower values (at around 9.000 Å), while Priabonian are centred around 9.020 Å. However, both value groups are in the intermediate pressure facies (between 9.000 and 9.040 Å) as shown in Figure 4 (the curve obtained is similar to the reference curve from Ryoike), suggesting an inferred geothermal gradient of 25-35°C/km (Guidotti and Sassi 1986).

### *3. Vein mineralogy, textural relationships and microthermometry*

Samples were collected within the RYSZ, previously described by Butler (1992), and consisting in an imbricate of basement slices and para-autochthonous sedimentary cover. This shear zone, lying directly below the frontal penninic nappe stack, has been considered as the map trace of the RT in this area (Trullenque 2005). All kinematic indicators measured in the field or deduced from microfabric analysis of calcite ultramylonites (Trullenque 2006), consistently show a WNW directed sense of transport, consistent with activity along the RT. No evidence of D<sub>2</sub> structures are found in this area.

Samples have been collected along strike slip fault planes dissecting basement slices and indicating a clear WNW directed sense of transport. These faults are clearly related to the first deformation phase D<sub>1</sub>. The chronology of the different fluid inclusion populations (Table 2) is a relative one with respect to their host mineral and their overgrowth (Mullis 1976).

Veins are mainly composed of small quartz crystals associated sometimes with calcite crystals. Only two-phase fluid inclusions (consisting of vapour and liquid at room temperature) were identified with the microscope. Fibre quartz is observed in the sample F72. In F92, two fluid inclusion assemblages are identified. The first one is a two-phase type in the

host quartz and probably of primary type, i.e. trapped during mineral growth. The second one is overprinting the first assemblage and probably of pseudo-secondary type. The true temperature of entrapment of the fluid inclusions, i.e. mineral growth, was constrained by intersecting the isochores of primary two-type phase fluid inclusions with the inferred geothermal gradient deduced from the K-white *b* cell dimension (Fig. 5). Isochores were calculated for the lower and upper homogenization temperature ( $T_{hi}$ ) with an average salinity of 5.6 and 13.8wt.% NaCl equivalent for samples F72 and F92, respectively.

## **5 Discussion**

The structural metamorphic map of the Alps (Oberhänsli et al. 2004) indicates lower sub-greenschist facies E of the RT and N of the Pelvoux massif. North of the Pelvoux massif, Ceriani et al. (2003) described an E-W metamorphic gradient on the E side of the RT. In the Briançonnais, they reported an increase from anchizonal to epizonal conditions from E to W. In the same area, the Dauphinois domain (in the footwall of the RT) shows epizonal metamorphic conditions. The Dauphinois domain in this area is only affected by one deformation phase, corresponding to the third deformation phase in the FPU (Ceriani 2001; Ceriani et al. 2001) and equivalent to  $D_1$  in our studied area (Trullenque 2005). The K-white *b* cell dimensions obtained by Ceriani et al. (2003) in the Dauphinois Domain are ranging between 9.000 and 9.030Å similar to those obtained in our study, indicating similar geothermal metamorphic gradient between the two areas.

Frey (1987) and Essene and Peacor (1995) showed that KI cannot be used as a precise geothermometer and only provide an approximate temperature range. In spite of this, attempts have been made to relate KI values to absolute temperatures. This was done in different low-grade metamorphic units by comparing the KI data with other geothermometers (Ferreiro Mählmann 1994, 1996; Merriman and Frey 1999; Mullis et al. 2002; Potel et al. 2006). Mullis

et al. (2002) have suggested a diagenesis – anchizone boundary in the Alps on the basis of a comparison of IC versus FI data. This allows to better define the range of temperature that the SE of the Pelvoux massif was subjected during tectonic evolution.

The KI values indicate that the Dauphinois domain in the SE of the Pelvoux massif underwent up to low anchizonal metamorphic conditions (Table 1; Fig. 2). According to Mullis et al. (2002), the boundary is linked to a temperature of around 230-240°C (similar to the compilation results from Ferreiro Mählmann (1994)). This can be compared to the temperature estimates obtained west of our studied area in the “grès de Champsaur” (W of Prapic). Waibel (1990) described quartz-prehnite±calcite veins in the “grès de Champsaur”. The country rock is dark green in colour, enriched in pumpellyite of variable composition, and to a lesser extent prehnite, at the expense of laumontite. Aprahamian (1988) described also mottled sandstone (faciès moucheté), the pale-coloured mottles being enriched in laumontite as cement and as partial replacement product of albitized clastic plagioclase and the darker areas being relatively enriched in chlorite cement. According to Frey et al. (1991) and Potel et al. (2002), the coexistence of zeolites (laumontite in this case) and prehnite-pumpellyite is restricted to a rather small P-T area below 240°C and therefore in the range obtained by using the correlation from Mullis et al. (2002).

Zircon FT data were gained from the turbiditic “grès de Champsaur” and the underlying Pelvoux crystalline basement (Seward et al. 1999). These data provide important information on the peak temperatures reached during Alpine metamorphism. For the zircon FT system, several estimates on the temperature range of the partial annealing zone exist (e.g. Yamada et al. 1995, Tagami et al. 1998, Yamada et al. 2007). Tagami et al. (1996) suggested a temperature range between 200 and 320°C to be appropriate, which covers the temperature range relevant to the metamorphic zonation based on illite “crystallinity” (e.g. Mullis et al. 2002). The combination of both methods therefore provides additional constraints on the

maximum temperature reached to the SE of the Pelvoux massif. In the Glarus Alps, the comparison between fluid inclusion data and zircon FT data suggests that zircon FT annealing in the Taveyanne sandstone (a lateral equivalent of the “grès de Champsaur”) only become detectable above 250 °C (Rahn 2001). The measured K-white mica *b* cell dimension values inferred intermediate geothermal gradient with 25-35°C/km (Merriman and Peacor 1999). This gradient seems to be a very conservative approach, however this result is similar to that we can found in the Dauphinois domain north of the Pelvoux Massif (Ceriani et al. 2003). Combining this information with the fluid inclusion data obtained in the Yret zone, a trapping temperature for the fluid inclusions of  $220 \pm 10^{\circ}\text{C}$  can be obtained (Figs. 5a & 5b). Consequently, the comparison of KI, FT and fluid inclusion leads to the conclusion that the SE of the Pelvoux massif was subjected to temperatures higher than 200°C, but lower than 250°C. This is higher than the estimation of temperature by Seward et al. (1999) who estimated that the burial temperature of the “grès de Champsaur” was not higher than 200°C. This implies metamorphic burial between 7 and 9 km. Neither our KI nor the FT data (Seward et al. 1999) reveal the presence of a metamorphic gradient from E to W in the SE of the Pelvoux massif as described by Aprahamian (1974). The absence of epizonal KI values in the Vallouise valley (Aprahamian 1974, 1988), moves the anchizone-epizone boundary to the N of the Pelvoux massif, where epizonal metamorphic conditions are observed (Ceriani et al. 2003). As mentioned by Ferreiro Málhmann and Frey (2012), one of the reasons of the lack of epizonal values, is that the KI values obtained by CIS calibration led to a broadening of the anchizone area.

The available metamorphic data from the south of the Pelvoux massif combined with the available deformation data allow us to deduce some conclusions concerning the tectono-metamorphic evolution in this area. A first important result provided by the KI, fluid inclusion and FT data is the fact that the Dauphinois domain exhibits lower metamorphic



conditions compared to the Penninic domain. According to the metamorphic map of the Alps, the Penninic domain west of the RT is metamorphosed under lower greenschist facies (Oberhänsli et al. 2004). Field evidences SE of the Pelvoux massif (this paper, Trullenque 2005), indicate that  $D_1$  corresponds to the first penetrative schistosity, marked by very fine-grained K-white mica, chlorite, quartz and albite. The metamorphic gradient observed and the formation of the fluid inclusions studied are related to this deformation phase and the burial heating (with a maximum of 9 km burial) was generated by the overthrust Penninic domain along the RT onto the Dauphinois domain. As mentioned above, the K-white mica *b* cell dimension values in our studied area SE of the Pelvoux massif, are similar to those obtained in the north by Ceriani et al. (2003). Therefore, the metamorphic gradient observed in the Penninic domain must be established before  $D_1$ , as observed by Ceriani et al. (2003) further to the N (the  $D_1$  observed SE of the Pelvoux massif correspond to the  $D_3$ , see above). So, we have no trace of an older metamorphic event.

North of the Pelvoux massif, the metamorphic grade is higher with epizonal conditions and may be explained by thicker Penninic units on top of the Dauphinois domain leading to higher degree of burial and therefore show a regional metamorphic gradient increasing from S to N. This is corroborated by the same pressure gradient observed north and south of the Pelvoux massif in the Dauphinois domain (same range of K-white mica *b* cell dimension).

Ferreiro Mählmann (2001) in the eastern Alps showed that in rocks submitted to a long metamorphic event (20 Ma) and a steady state heat flow, the smectite content in the anchizone is between 0 and 5% (90% of the samples without smectite), and that under stable thermal conditions (equilibrium), KI can be used as a thermometer. In this region, Henrichs (1993) reported K-white mica *b* cell dimension values between 9.000 and 9.022 Å and the compilation of the Ferreiro Mählmann et al. (2012) shows a normal to low geothermal gradient (30°C/km). Comparison of our results with KI and K-white mica *b* cell dimension

values will suggest that the Dauphinois Domain has been submitted to a relative long heating time like in the eastern Alps.

## **Conclusion**

The tectono-metamorphic history of the Dauphinois domain in the SE of the Pelvoux is similar that described by Ceriani et al. (2003) in the north. Peak metamorphic conditions in the Dauphinois domain are reached during the overthrusting of the Penninic units during D<sub>1</sub> top-WNW directed thrusting along the RT. The metamorphism is characterized by temperatures below 250°C and higher than 200°C and a metamorphic gradient between 25 and 35°C, and a long time event. This range of temperature is compatible with the FT data published by Seward et al. (1999) indicating that the burial temperature in the region was lower than 250°C. Based on our KI values and the mineral paragenese observed in the W of the “grès de Champsaur”, no E-W metamorphic zonation as described by Aprahamian (1974, 1988) is observed. But, in the studied area, the grade of metamorphism in the Dauphinois Domain is lower than in the northern of the Pelvoux massif (Ceriani et al. 2003) confirming the N-S metamorphic zonation described by Aprahamian (1974, 1988). This is also outlined by the zircon FT ages indicating an increase in age primarily from the north to the south (Fügenschuh and Schmid, 2003) and supports their hypothesis that the more southerly located areas were less deeply buried and hence less exhumed. Like proposed by Ceriani et al. (2001) and Fügenschuh and Schmid (2003), the overthrust along the RT of the Penninic units may caused burial and metamorphism in the external Dauphinois units.

## **Acknowledgements**

This manuscript benefited greatly from constructive and helpful reviews and comments from M. Rahn and R. Ferreiro Mählmann.

## References

- Apps, G.M., Peel, F. & Elliott, T. (2004). The structural setting and palaeogeographical evolution of the Gres d'Annot Basin. Deep-water sedimentation in the Alpine Basin of SE France; new perspectives on the Gres d'Annot and related systems. *Geological Society Special Publication*, 221, 65-96.
- Aprahamian, J. (1974). La cristallinité de l'illite et les minéraux argileux en bordure des massifs cristallins externes de Belledonne et du Pelvoux. *Géologie Alpine*, 50, 5-15.
- Aprahamian, J. (1988). Cartographie du métamorphisme faible à très faible dans les Alpes françaises externes par l'utilisation de la cristallinité de l'illite. *Geodinamica Acta*, 2, 25-32.
- Árkai P. (1991). Chlorite crystallinity: an empirical approach and correlation with illite crystallinity, coal rank and mineral facies as exemplified by Palaeozoic and Mesozoic rocks of northeast Hungary. *Journal of Metamorphic Geology*, 9, 723-734.
- Árkai, P., Sassi, F.P. & Sassi, R. (1995). Simultaneous measurements of chlorite and illite crystallinity: a more reliable tool for monitoring low- to very low grade metamorphism in metapelites. A case study from the Southern Alps (NE Italy). *European Journal Mineralogy*, 7, 1115-1128.
- Árkai, P., Faryad, S.W., Vidal, O. & Balogh, K. (2003). Very low-grade metamorphism of sedimentary rocks of the Meliata unit, Western Carpathians, Slovakia: Implications of phyllosilicate characteristics. *International Journal of Earth Sciences*, 92, 68-85.

437 Brown, P.E., & Lamb, W.M. (1989). P-V-T properties of fluids in the system  
 438  $\text{H}_2\text{O} \pm \text{CO}_2 \pm \text{NaCl}$ : New graphical presentations and implications for fluid inclusion  
 439 studies. *Geochimica Cosmochimica Acta*, 53, 1209-1221.

440 Burke, E.A.J. (2001). Raman microspectrometry of fluid inclusions. *Lithos*, 55, 139-158.

441 Bürgisser, J. (1998). Deformation in foreland basins of the Western Alps (Pelvoux massif, SE  
 442 France); significance for the development of the Alpine arc. ETH, Zürich, 151 pp.

443 Butler, R.W.H. (1989). The influence of pre-existing basin structure on thrust system  
 444 evolution in Western Alps. *Geological Society Special Publications*, 44, 105-122.

445 Butler, R.W.H. (1992). Thrust zone kinematics in a basement-cover imbricate stack; eastern  
 446 Pelvoux Massif, French Alps. *Journal of Structural Geology*, 14, 29-40.

447 Ceriani, S. (2001). A combined study of structure and metamorphism in the frontal Penninic  
 448 units between the Arc and the Isère valleys (Western Alps): Implications for the  
 449 geodynamics evolution of the Western Alps. Unpublished PhD thesis, Universität Basel,  
 450 196 pp.

451 Ceriani, S., Fügenschuh, B., Potel, S. & Schmid, S.M. (2003). The tectono-metamorphic  
 452 evolution of the Frontal Penninic units of the Western Alps: correlation between low-  
 453 grade metamorphism and tectonic phases. *Schweizerische Mineralogische und*  
 454 *Petrographische Mitteilungen*, 83, 111-131.

455 Ceriani, S., Fügenschuh, B. & Schmid, S.M. (2001). Multi-stage thrusting at the “Penninic  
 456 Front” in the Western Alps between Mont Blanc and Pelvoux massifs. *International*  
 457 *Journal of Earth Sciences*, 90, 685-702.

458 Coward, M.P., Gillcrist, R. & Trudgill, B. (1991). Extensional structures and their tectonic  
 459 inversion in the Western Alps. *Geological Society Special Publications*, 5, 93-112.

460 Dalla Torre, M., Stern, W.B. & Frey, M. (1994). Determination of white K-mica polytype  
 461 ratios: comparaison of different XRD methods. *Clay Minerals*, 29, 717-726.

462 Davies, V.M. 1982: Interaction of thrusts and basement faults in the French external Alps.  
 463 *Tectonophysics*, 88, 325-331.

464 Debrand-Passard, S., Courbouleix, S. & Lienhardt, M.-J. (1984). Synthèse géologique du  
 465 Sud-Est de la France. *Mémoire du Bureau de recherches géologiques et minières*, 126pp.

466 Desmons, J., Compagnoni, R. & Cortesogno, L. (1999). Alpine metamorphism of the Western  
 467 Alps: II. High-P/T and related pre-greenschist metamorphism. In: Frey, M., Desmons, J.  
 468 & Neubauer, F. (Eds.): The new metamorphic map of the Alps. *Schweizerische*  
 469 *Mineralogische und Petrographische Mitteilungen*, 79, 111-134.

470 Ernst, W.G. (1963). Significance of phengitic micas from low grade schists. *American*  
 471 *Mineralogist*, 48, 1357-1373.

472 Essene, E.J. & Peacor, D.R. (1995). Clay mineral thermometry – a critical perspective. *Clays*  
 473 *Clay Mineral*, 43, 540-553.

474 Ferreiro Mählmann, R. (1994). Zur Bestimmung von Diagenesehöhe und beginnender  
 475 Metamorphose-Temperaturgeschichte und Tektogenese des Austroalpins und  
 476 Süpenninikums in Vorarlberg und Mittelbünden. Universität Frankfurt, *Frankfurter*  
 477 *Geowissenschaftliche Arbeiten, Serie C 14*, 498 pp.

478 Ferreiro Mählmann, R. (1996). The pattern of diagenesis and metamorphism by vitrinite  
 479 reflectance and illite-“crystallinity” in Mittelbünden and in the Oberhalbstein. Part2:  
 480 Correlation of coal petrographical and of mineralogical parameters. *Schweizerische*  
 481 *Mineralogische und Petrographische Mitteilungen*, 76, 23-46.

482 Ferreiro Mählmann, R. (2001). Correlation of very low-grade data to calibrate a thermal  
 483 maturity model in a nappe tectonic setting, a case study from the Alps. *Tectonophysics*,  
 484 334, 1-33.

485 Ferreiro Mählmann, R. & Frey, M. (2012). “Standardisation, calibration and correlation of the  
486 Kübler-Index and the vitrinite/bituminite reflectance measure: a inter-laboratory and field  
487 related study”. *Swiss Journal of Geosciences*, this volume.

488 Ferreiro Mählmann, R., Bozkaya, O., Potel, S., Le Bayon, R., Šegvić, B. & Nieto García, F.  
489 (2012). The pioneer work of Bernard Kübler and Martin Frey in very low-grad  
490 metamorphic terranes: Paleo-geothermal potential of Kübler-Index/organic matter  
491 reflectance correlation – a review. *Swiss Journal of Geosciences*, this volume.

492 Frey, M. (ed.) (1987). Low Temperature Metamorphism. Blackie & Son, Glasgow and  
493 London, 351 pp.

494 Frey, M., de Capitani, C. & Liou, J.G. (1991). A new petrogenetic grid for low-grade  
495 metabasites. *Journal of Metamorphic Geology*, 9, 497-509.

496 Frey, M., Desmons, J. & Neubauer, F. (Eds.) (1999). The new metamorphic map of the Alps.  
497 *Schweizerische Mineralogische und Petrographische Mitteilungen*, 79, 230 pp.

498 Frey, M., Teichmüller, M., Teichmüller, R., Mullis, J., Künzi, B., Breitschmid, A., Gruner, U.  
499 & Schwizer, B. (1980). Very low-grade metamorphism in external parts of the Central  
500 Alps: Illite crystallinity, coal rank and fluid inclusion data. *Eclogae Geologicae*  
501 *Helvetiae*, 73, 173-203.

502 Fügenschuh, B. & Schmid, S. (2003). Late stages of deformation and exhumation of an  
503 orogen constrained by fission-track data: A case study in the Western Alps. *Geological*  
504 *Society of America Bulletin*, 115, 1425-1440.

505 Gillcrist, R., Coward, M. & Mugnier, J.L. (1987). Structural inversion and its controls;  
506 examples from the Alpine Foreland and the French Alps. *Geodinamica Acta*, 1, 5-34.

507 Guggenheim, S.Jr, Bain, D.C., Bergaya, F., Brigatti, M.F., Drits, V.A., Eberl, D.D., Formoso,  
508 M.L.L., Galan, E., Merriman, R.J., Peacor, D.R., Stanjek, H. & Watanabe, T. (2002).  
509 Report of the association internationale pour l'étude des argiles (AIPEA) nomenclature

510 committee for 2001: order, disorder and crystallinity in phyllosilicates and the use of the  
 511 'crystallinity index'. *Clays and Clay Minerals*, 50, 406-409.

512 Guidotti, C.V. & Sassi, F.P. (1986). Classification and correlation of Metamorphic Facies  
 513 Series by Means of Muscovite  $b_0$  data from Low-Grade Metapelites. *Neues Jarbuch*  
 514 *Mineralogie Abteilunghefte*, 153, 363-380.

515 Guidotti, C.V., Sassi, F.P. & Blencoe, J.G. (1989). Compositional controls on the a and b cell  
 516 dimensions of 2M<sub>1</sub> Muscovites. *European Journal of Mineralogy*, 1, 71-84.

517 Gupta, S. (1997). Tectonic control on paleovalley incision at the distal margin of the early  
 518 Tertiary Alpine foreland basin, southeastern France. *Journal of Sedimentary Research*,  
 519 67, 1030-1043.

520 Hall D. L., Sterner S. M. & Bodnar R. J. (1988). Freezing point depression of NaCl-KCl-  
 521 H<sub>2</sub>O solutions. *Economic Geology*, 83, 197-202.

522 Henrichs, C. (1993). Sedimentpetrographische Untersuchungen zur Hochdiagenese in der  
 523 Kössen-Formation (Ober Trias) der westlichen Ostalpen und angrenzenden  
 524 Südalpengebiete. *Bochumer geologische und geo-technische Arbeiten* 40, 206 pp.

525 Huyghe, P. & Mugnier, J.L. (1995). A comparison of inverted basins of the southern North  
 526 Sea and inverted structures of the external Alps. *Geological Society Special Publications*,  
 527 88, 339-353.

528 Kisch, H.J., Árkai, P. & Brime, C. (2004). On the calibration of illite Kübler index (illite  
 529 'crystallinity'). *Schweizerische Mineralogische und Petrographische Mitteilungen*, 84,  
 530 323-331.

531 Kretz, R. (1983). Symbols for rock-forming minerals. *American Mineralogist*, 68, 277-279.

532 Kübler, B. (1964). Les argiles, indicateurs de métamorphisme. *Institut Français Pétrole*, 19,  
 533 1093-1112.

534 Kübler, B. (1968). Evaluation quantitative du métamorphisme par la cristallinité de l'illite.  
 535 Etat des progrès réalisés ces dernières années. *Bulletin Centre Recherche Pau, S.N.P.A.*,  
 536 2, 385-397.

537 Lazarre, J., Tricart, P., Courrioux, G. & Ledru, P. (1996). Héritage téthysien et polyphasage  
 538 alpin; réinterprétation tectonique du "synclinal" de l'aiguille de Morges (massif du  
 539 Pelvoux, Alpes occidentales, France). *Comptes Rendus de l'Académie des Sciences, Série*  
 540 *II. Sciences de la Terre et des Planètes*, 323, 1051-1058.

541 Merriman, R.J., Roberts, B. & Peacor, D.R. (1990). A transmission electron microscope study  
 542 of white mica crystallite size distribution in a mudstone to slate transitional sequence,  
 543 North Wales, U. K. *Contributions to Mineralogy & Petrology*, 106, 27-40.

544 Merriman, R.J. & Peacor, D.R. (1999). Very low-grade metapelites: mineralogy, microfabrics  
 545 and measuring reaction progress. In: Frey, M. & Robinson, D. (Eds.): *Low-Grade*  
 546 *Metamorphism*. Blackwell Science, London, 10-60.

547 Mullis, J. (1976). Das Wachstumsmilieu der Quarzkristalle im Val d'Illiez (Wallis, Schweiz).  
 548 *Schweizerische Mineralogische und Petrographische Mitteilungen*, 56, 219-268.

549 Mullis, J. (1987). Fluid inclusion studies during very low-grade metamorphism. In: Frey, M.  
 550 (Ed.): *Low temperature metamorphism*. Glasgow, Blackie, 162-199.

551 Mullis, J. J., Rahn, M. K. W., Schwer, P., de Capitani, C., Stern, W.B. & Frey, M. (2002).  
 552 "Correlation of fluid inclusion temperatures with illite "crystallinity" data and clay  
 553 mineral chemistry in sedimentary rocks from the external part of the Central Alps."  
 554 *Schweizerische Mineralogische und Petrographische Mitteilungen*, 82, 325-340.

555 Oberhänsli, R., Bousquet, R., Engi, M., Goffé, B., Gosso, G., Handy, M., Höck, V., Koller,  
 556 F., Lardeaux, J.-M., Polino, R., Rossi, P., Schuster, R., Schwarz, S. & Spalla, M.I.  
 557 (2004). *Metamorphic structure of the Alps (1:1'000'000)*, Commission for the Geological  
 558 Map of the World (UNSECO), Paris.



559 Perriaux, J. & Uselle, J.P. (1968). Quelques données sur la sédimentologie des grès du  
560 Champsaur (Hautes-Alpes). *Géologie Alpine*, 44, 329-332.

561 Potel, S., Schmidt, S.Th. & de Capitani, C. (2002). Composition of pumpellyite, epidote and  
562 chlorite from New Caledonia – How important are metamorphic grade and whole-rock  
563 composition? *Schweizerische Mineralogische und Petrographische Mitteilungen*, 82,  
564 229-252.

565 Potel S., Ferreira Mählmann R., Stern W.B., Mullis J. & Frey M. (2006). Very low-grade  
566 metamorphic evolution of pelitic rocks under high-pressure/low-temperature conditions,  
567 NW New Caledonia (SW Pacific). *Journal of Petrology*, 47, 991-1015.

568 Rahn, M.K.W. (2001). The metamorphic and exhumation history of the Helvetic Alps,  
569 Switzerland, as revealed by apatite and zircon fission tracks. Unpublished Habilitation  
570 thesis, Albert-Ludwigs-Universität Freiburg, 140pp.

571 Ravenne, C., Vially, R., Riche, P. & Tremolieres, P. (1987). Sédimentation et tectonique dans  
572 le bassin marin Eocene supérieur-Oligocene des Alpes du Sud. *Revue de l'Institut*  
573 *Français du Pétrole*, 42, 529-553.

574 Sassi, F.P. & Scolari, A. (1974). The  $b_0$  of the potassic white micas as a barometric indicator  
575 in low-grade metamorphism of pelitic schists. *Contributions to Mineralogy and*  
576 *Petrology*, 45, 143-152.

577 Schmid, S.M., Fügenschuh, B., Kissling E. & Schuster, R. (2004). Tectonic map and overall  
578 architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae* 97, 93-117.

579 Seward, D., Ford, M., Bürgisser, J., Lickorish, H., Williams, E.A. & Meckel III L.D. (1999).  
580 Preliminary report on fission tracks studies in the Pelvoux area, SE France. *Memorie di*  
581 *Scienze Geologiche*, 51, 25-31.

582 Sue, C., Tricart, P., Dumont, T. & Pecher, A. (1997). Raccourcissement polyphase dans le  
583 massif du Pelvoux (Alpes occidentales) : exemple du chevauchement de socle de Villard-

584 Notre-Dame. *Comptes Rendus de l'Académie des Sciences, Série II. Sciences de la Terre*  
585 *et des Planètes*, 324, 847-854.

586 Tagami, T., Galbraith, R. F., Yamada, R. & Laslett, G. M. (1998). Revised annealing kinetics  
587 of fission tracks in zircon and geological implications. In P. Van den haute, & F. De  
588 Corte (Eds.), *Advances in fission-track geochronology*: Kluwer academic publishers,  
589 Dordrecht, The Netherlands, 99-112.

590 Tricart, P. (1986). Le Chevauchement de la zone briançonnaise au Sud-Est du Pelvoux; clé  
591 des rapports zone externe - zones internes dans les Alpes occidentales. *Bulletin de la*  
592 *Société Géologique de France, Huitième Série*, 2, 233-244.

593 Tricart, P., Bourbon, M., Chenet, P. Y., Cros, P., Delorme, M., Dumont, T., Graciansky, P.C.,  
594 Lemoine, M., Megard, Galli, J. & Richez, M. (1988). Tectonique synsédimentaire  
595 triasico-jurassique et rifting téthysien dans la nappe briançonnaise de Peyre-Haute (Alpes  
596 occidentales). *Bulletin de la Société Géologique de France*, 4, 669-680.

597 Tricart, P., Bouillin, J.P., Dick, P., Moutier, L. & Xing, C. (1996). Le faisceau de failles de  
598 haute-Durance et le jeu distensif du front briançonnais au SE du Pelvoux (Alpes  
599 occidentales). *Comptes Rendus de l'Académie des Sciences, Série II. Sciences de la Terre*  
600 *et des Planètes*, 323, 251-257.

601 Tricart, P. (2004). From extension to transpression during the final exhumation of the Pelvoux  
602 and Argentera massifs, Western Alps. *Eclogae Geologicae Helvetiae*, 97, 429-439.

603 Tricart, P., Schwartz, S., Sue, C., Poupeau, G. and Lardeaux, J.M. (2001). La dénudation  
604 tectonique de la zone Ultradaphinoise et l'inversion du front Briançonnais au Sud Est du  
605 Pelvoux (Alpes Occidentales); une dynamique Miocène à actuelle. *Bulletin de la Société*  
606 *Géologique de France*, 172, 49-58.

607 Trullenque, G. (2005). Tectonic and microfabric studies along the Penninic Front between  
608 Pelvoux and Argentera Massifs (Western Alps, France). Unpublished PhD thesis,  
609 Universität Basel, 301 pp.

610 Trullenque, G., Kunze, K., Heilbronner, R., Stünitz, H. & Schmid, S. (2006). Microfabrics of  
611 calcite ultramylonites as records of coaxial and non-coaxial deformation kinematics:  
612 Examples from the Rocher de l'Yret shear zone (Western Alps). *Tectonophysics*, 424, 69-  
613 97.

614 Waibel, A.F. (1990). Sedimentology, petrographic variability, and very-low-grade  
615 metamorphism of the Champsaur sandstone (Paleogene, Hautes-Alpes, France).  
616 Evolution of volcanoclastic foreland turbidites in the external Western Alps. Unpublished  
617 PhD thesis, Université de Genève, 140pp.

618 Warr, L.N. & Rice, A.H. (1994). Interlaboratory standardization and calibration of clay  
619 mineral crystallinity and crystallite size data. *Journal of Metamorphic Geology*, 12, 141-  
620 152.

621 Yamada, R., Tagami, T., Nishimura, S. & Ito, H. (1995). Annealing kinetics of fission tracks  
622 in zircon: an experimental study. *Chemical Geology (Isotope Geoscience Section)*, 122,  
623 249-258.

624 Yamada, R., Galbraith, R.F., Murakami, M., Tagami, T. (2007). Statistical modelling of  
625 annealing kinetics of fission-tracks in zircon; reassessment of laboratory experiments.  
626 *Chemical Geology*, 236, 75-91.

627 Zhang, Y. & Frantz, J. D. (1987). Determination of the homogenization temperatures and  
628 densities of supercritical fluids in the system NaCl-KCl-CaCl<sub>2</sub>-H<sub>2</sub>O using synthetic fluid  
629 inclusions. *Chemical Geology*, 64, 335-350.

630

**Fig. 1:** (a) Simplified geological overview of the arc of the western Alps (A: Argentera massif, CM: Combeynot massif, MB: Mont Blanc massif, P: Pelvoux massif, R: Rhone-Simplon line, T: Tonale line); after Froitzheim et al. (1996), Ceriani et al. (2000) and Schmidt et al. (2004). (b) Tectonic map along the eastern rim of the Pelvoux Massif compiled from 1) geological maps BRGM (1/50 000): La Grave, Briançon, St Christophe en Oisans, Guillestre, Orcières and Embrun and 2) Tricart (1986). Points Yr, Fo, Be, Cha, Do and DoF refer to samples studied, collected at the eastern rim of the Pelvoux Massif, in the Yret, Fournel, Beassac, Chambran, Dormillouse and Dormillouse-Fangeas valleys, respectively. RT: Roselend Thrust. RYSZ: Rocher de l'Yret shear zone.

**Fig. 2:** Distribution and values of Kübler index (KI) and Árkai index (ÁI) in the studied area. Due to the proximity of the samples Do4,4a,4b; Do5a,c; DoF1a,b; Fo1b,c,e; Fo2b,c and Fo3a,b,c the values are shown as averages. RT: Roselend Thrust.

**Fig. 3:** Correlation between Kübler index (KI) and Árkai index (ÁI) (a) and the  $2M_1/1M_d$  illite polytype ratio (b), all derived from air-dried mounts.

**Fig. 4:** Cumulative curves of K-white mica *b* cell dimensions for 21 anchizonal samples from our study area (in bold) with reference curves from Sassi and Scolari (1974) and Guidotti and Sassi (1986).

**Fig. 5:** Depth-Temperature diagrams with isochores representing the higher and the lower calculated molar volumes for vapour-rich fluid inclusions and the mean isochores in samples F72 (a) and F92 (b) from the Yret zone. The dashed lines represent the range of geothermal

655 gradients from 25°C/km and 35°C/km as deduced from the K-white mica *b* cell dimensions.

656 The thick curve represents the liquid-gas reaction curve of water. CP: critical point of water.

657

658 **Table 1:** Samples identification, stratigraphic age, Illite Kübler index and chlorite

659 "crystallinity" values of the <2µm grain-size fraction samples (data in  $\Delta^\circ 2\theta$ ), percent of 2M<sub>1</sub>

660 polytypes and K-white mica *b* cell dimension data.

661

662 **Table 2:** Fluid inclusion data of two quartz samples from the Yret Zone, Western French

663 Alps.

664

665

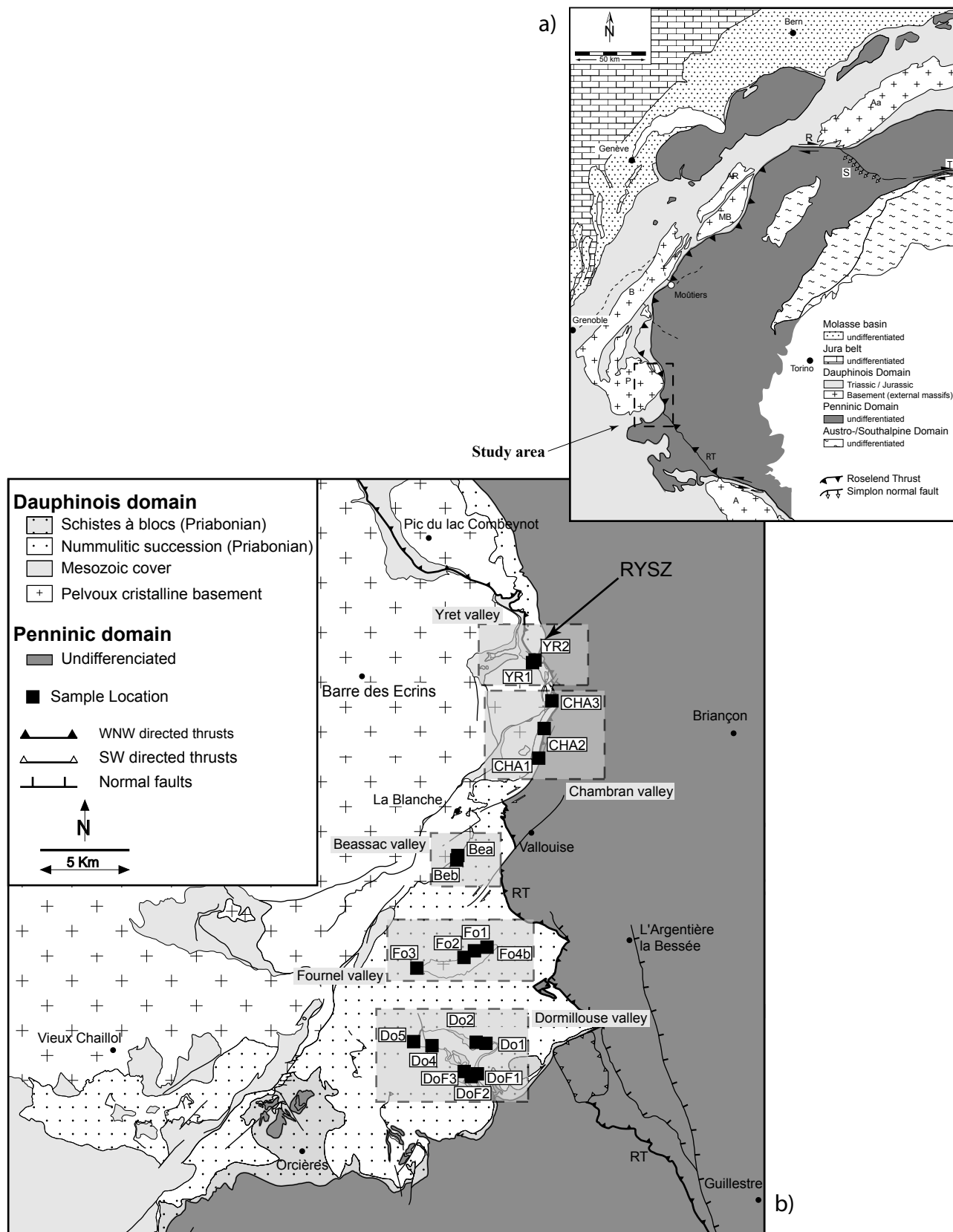


Figure 1

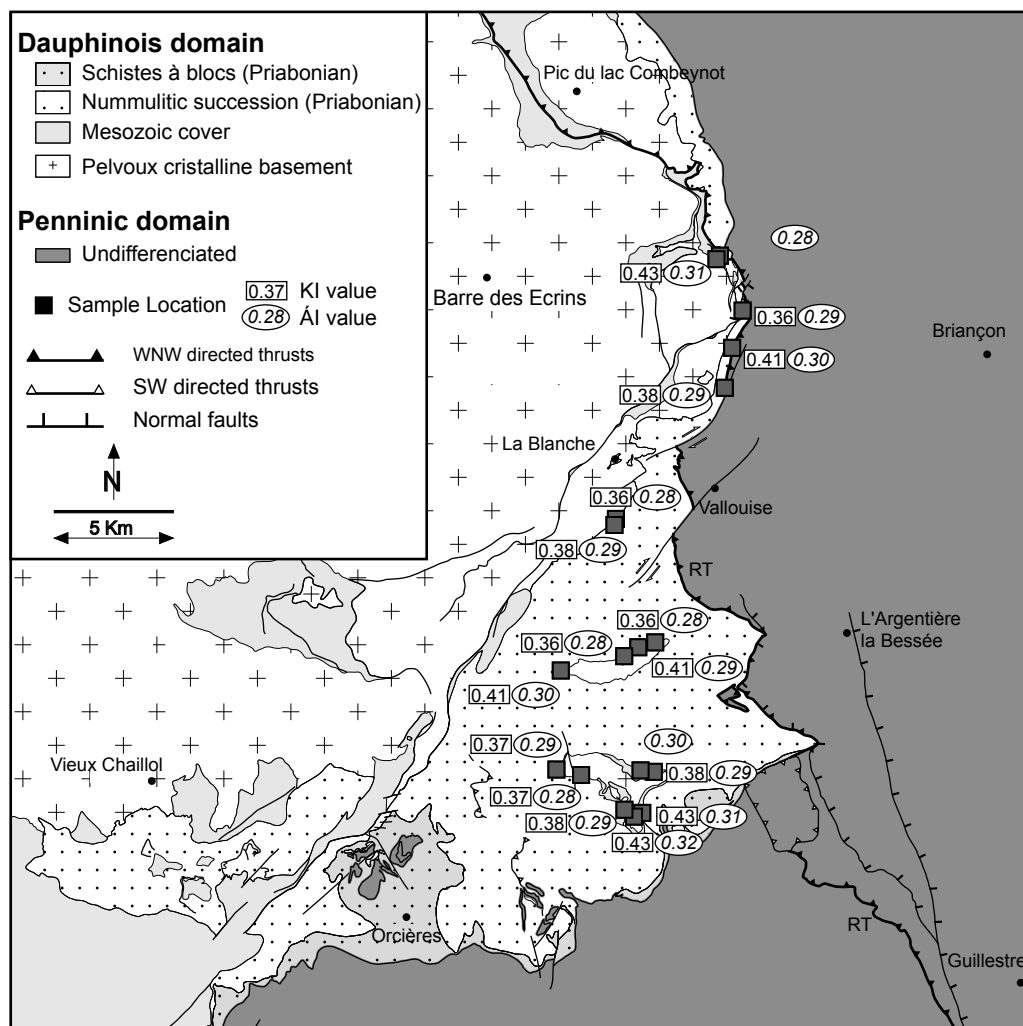


Figure 2

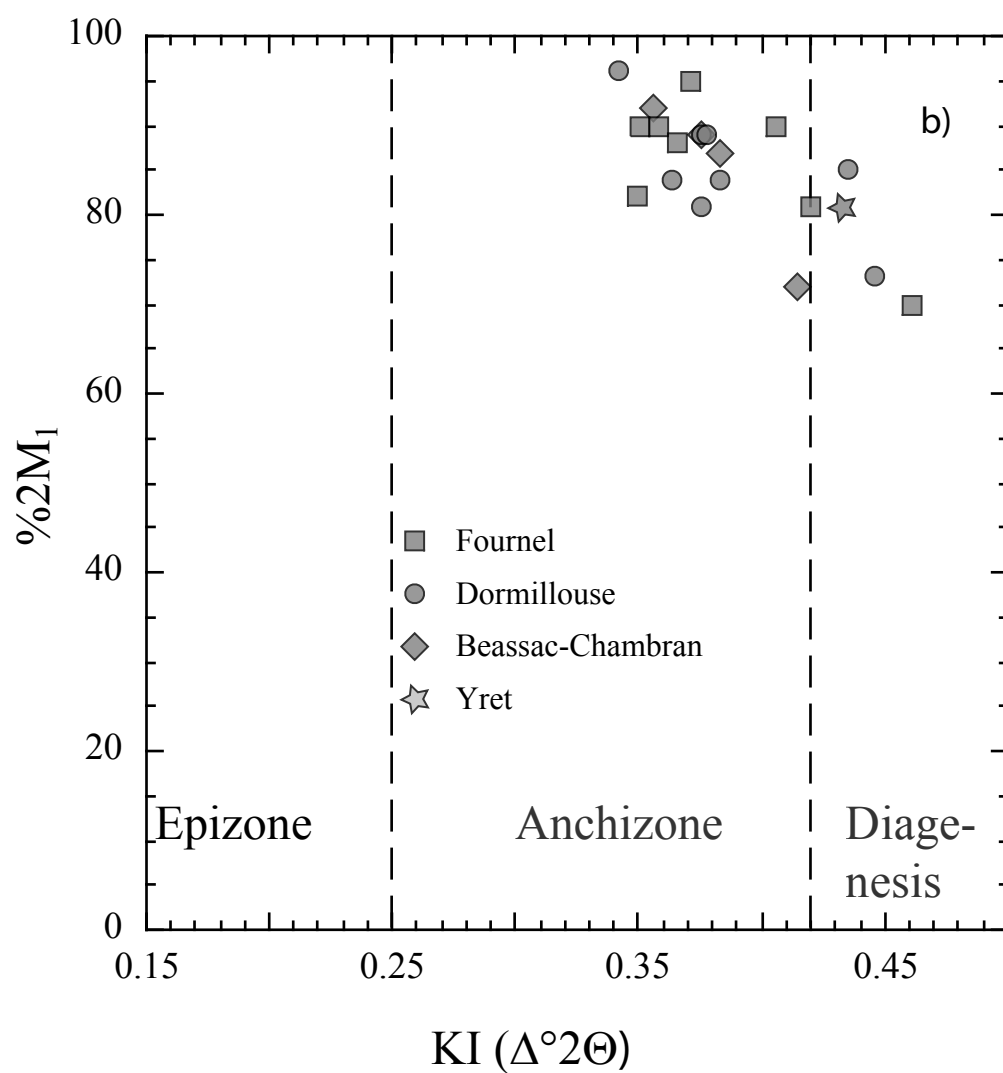
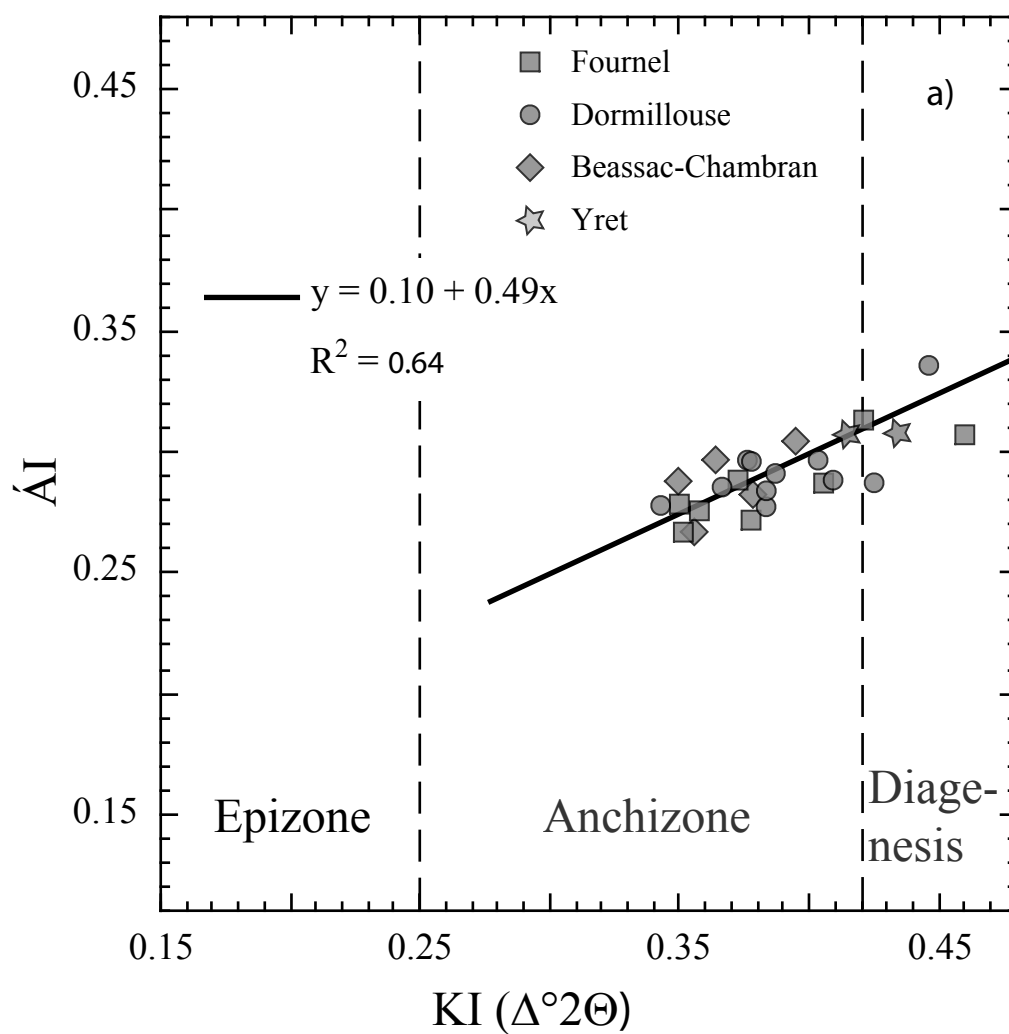


Figure 3



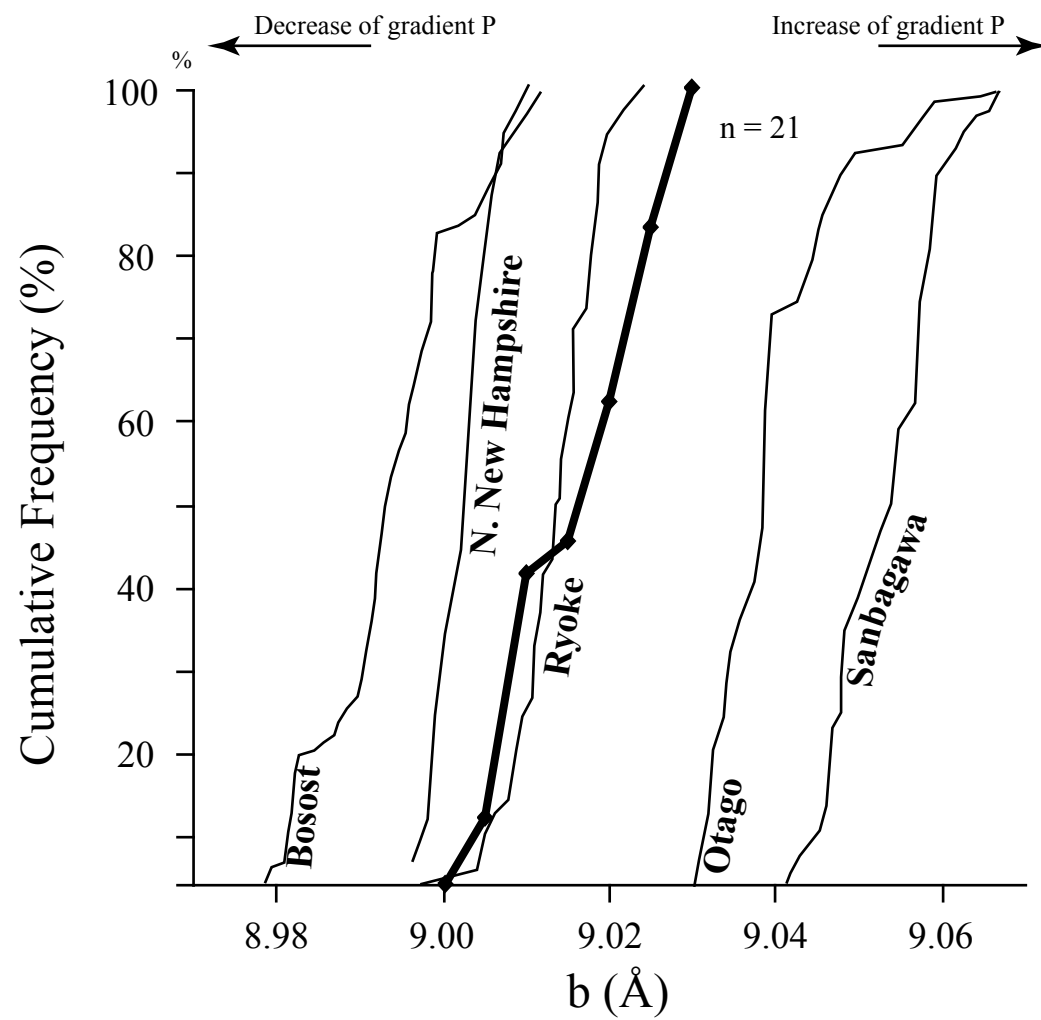


Figure 4

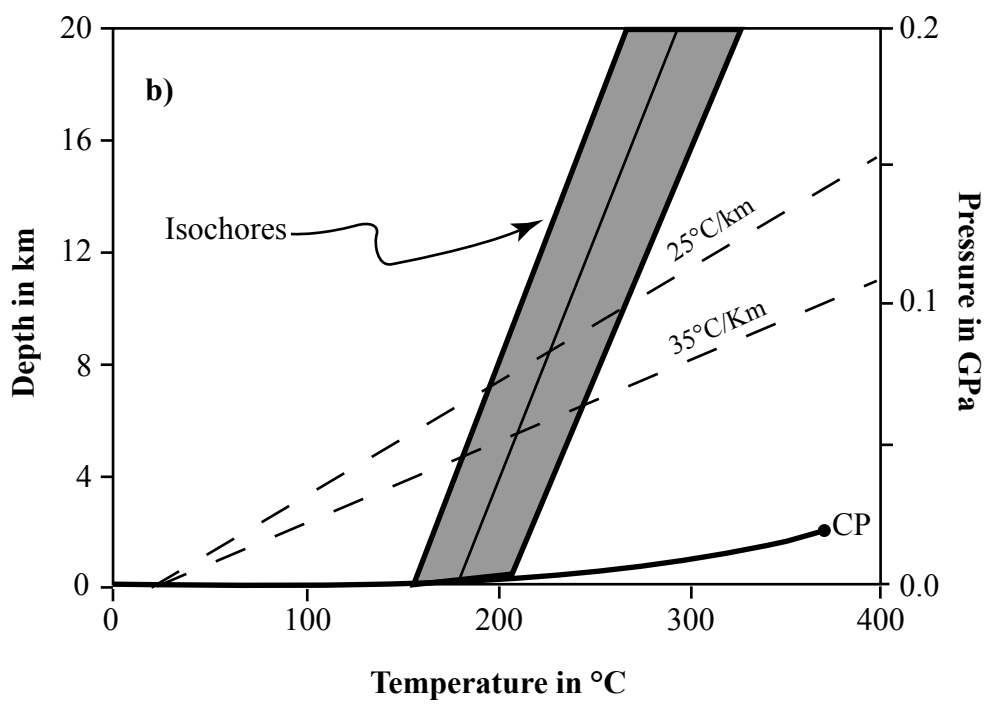
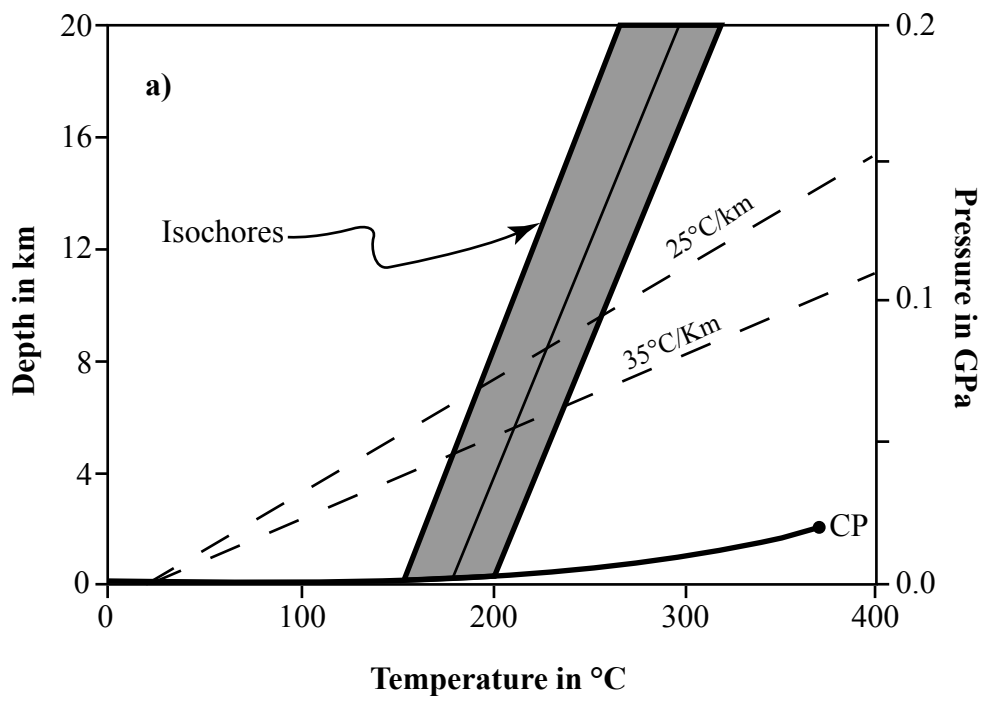


Figure 5

Sample	Sratigraphic age	Elevation in m	IC <sub>Giessen</sub> $\Delta^{\circ}2\Theta$	KI $\Delta^{\circ}2\Theta$	1 $\sigma$ $\Delta^{\circ}2\Theta$	ChC $\Delta^{\circ}2\Theta$	$\acute{A}I$ $\Delta^{\circ}2\Theta$	1 $\sigma$ $\Delta^{\circ}2\Theta$	%2M <sub>1</sub>	b (Å)
Bea	Priabonian	1350	0.31	0.36	0.00	0.30	0.28	0.00	92	9.024
Beb	Priabonian	1370	0.33	0.38	0.00	0.30	0.29	0.01	87	9.009
CHA1	Priabonian	1700	0.33	0.38	0.01	0.30	0.29	0.01	89	9.008
CHA2	Priabonian	1710	0.36	0.41	0.00	0.32	0.30	0.01	72	9.015
CHA3	Priabonian	1720	0.32	0.36	0.00	0.30	0.29	0.01	84	9.001
Do1	Mesozoic Cover	1500	0.33	0.38	0.00	0.30	0.29	0.00	81	8.998
Do2	Mesozoic Cover	1520	0.35	0.40	0.00	0.32	0.30	0.01	-	9.006
Do4a	Priabonian	1835	0.33	0.38	0.00	0.30	0.29	0.01	-	9.026
Do4b	Priabonian	1835	0.34	0.39	0.01	0.30	0.29	0.01	-	9.025
Do4	Priabonian	1840	0.30	0.34	0.01	0.29	0.28	0.01	96	9.010
D05a	Mesozoic Cover	2100	0.33	0.38	0.00	0.31	0.30	0.01	89	9.004
Do5c	Mesozoic Cover	2105	0.32	0.37	0.01	0.31	0.29	0.01	79	9.007
DoF1a	Mesozoic Cover	1700	0.35	0.41	0.00	0.32	0.30	0.01	-	-
DoF1b	Mesozoic Cover	1700	0.38	0.45	0.00	0.33	0.32	0.02	73	-
DoF2	Priabonian	2400	0.37	0.43	0.00	0.34	0.32	0.02	85	-
DoF3	Priabonian	2200	0.33	0.38	0.00	0.30	0.29	0.00	84	9.025
Fo1b	Priabonian	1800	0.32	0.37	0.00	0.30	0.28	0.01	88	9.018
Fo1c	Priabonian	1740	0.31	0.35	0.00	0.29	0.28	0.02	90	9.010
Fo1e	Priabonian	1740	0.33	0.38	0.00	0.30	0.28	0.01	-	-
Fo2b	Priabonian	1760	0.32	0.37	0.00	0.30	0.28	0.01	95	9.017
Fo2c	Priabonian	1760	0.31	0.36	0.00	0.30	0.29	0.01	90	9.019
Fo3a	Priabonian	2100	0.31	0.35	0.00	0.29	0.28	0.01	82	9.028
Fo3b	Priabonian	2100	0.36	0.42	0.00	0.32	0.31	0.01	81	9.025
Fo3c	Priabonian	2100	0.39	0.46	0.02	0.32	0.31	0.01	70	-
Fo4b	Priabonian	1640	0.35	0.41	0.00	0.31	0.29	0.01	90	9.016
YR1	Priabonian	2700	0.37	0.43	0.01	0.33	0.31	0.00	81	9.021
YR2	Priabonian	2700	0.34	0.39	0.01	0.29	0.28	0.01	-	-

IC= illite “crystallinity” measured in Giessen. KI= Kübler Index. ChC= chlorite “crystallinity” of the 002 chlorite peak.  $\acute{A}I$ = Árkai Index. %2M<sub>1</sub>= percent of 2M<sub>1</sub> polytypes. b(Å)= K-white mica *b* cell dimension.

**Table 2**

1 Locality	2 FP	3 HM	4 IT	5 n <sub>I</sub>	6 V%	7 Tm <sub>ICE</sub>	8 Th <sub>I</sub>	9 H <sub>2</sub> O mole %	10 NaCl mole %
F72	1	FQ	P	66	5	-3.5 ± 0.6	176.6 ± 18.3	94.5	5.6
F92	1	VQ	Ps II	22	5	-6.9 ± 0.9	182.4 ± 15.5	89.8	10.2
“	2	VQ	P	3	5-10	-9.6 ± 0.9	172.3 ± 10.0	87.2	13.8

(1) Locality number. (2) FP = Fluid inclusion population. (3) HM = Host mineral. - FQ = Fibre quartz; VQ = Vein quartz. (4) IT = Inclusion type. – Ps II = Pseudosecondary fluid inclusions; P = Primary fluid inclusions. (5) n<sub>I</sub> = Number of measured fluid inclusions. (6) V % = Volume-% of the volatile part estimated at room temperature. (7) Tm<sub>ice</sub> = Melting temperature of ice (°C). - *First number* = mean value; *second number* = standard deviation. (8) Th<sub>I</sub> = Homogenization temperature of fluid inclusions. - First number = mean value; second number = standard deviation. (9) and (10) = Approximate mole-% H<sub>2</sub>O and NaCl (equivalents).