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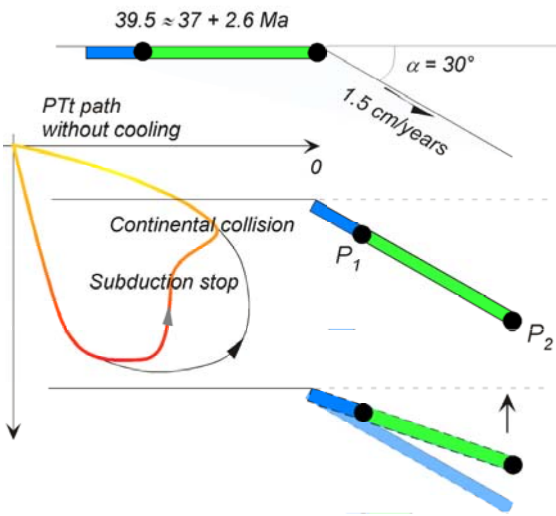

Some comments on the implication of simple thermal modelling of the "Préalpes médianes" in the northwestern Swiss Alps

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Some comments on the implication of simple thermal modelling of the "Préalpes médianes" in the northwestern Swiss Alps

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Abstract

Metamorphic temperatures and ages of the Préalpes Médianes units (Switzerland) are compared to a simple geometrical thermal modelling using finite difference method. Even if the used model is simple, the order of magnitude of maximum temperature ages agreed with available data. The model confirmed that the internal part of the PM might have reached 250-300ºC. The calculated ages of 26 Ma for the maximum temperature is found to be compatible with the ages of 27 Ma deduced from illites dating.

Keywords: Thermal modelling, illite crystallinity, Préalpes Médianes, metamorphic ages.

1. Introduction

P-T-t paths modelling of Alpine metamorphism do exist (OXBURGH and TURCOTTE, 1974, OXBURGH and ENGLAND, 1980; ENGLAND, 1978; DAVY and GILLET, 1986, WERNER, 1980; GRASEMANN and MANCKTELOW, 1993), but no ones are dedicated to the incipient metamorphism in the Préalpes. By using a simple 1D finite difference model it is possible to estimate the time-temperature evolution along several profiles. Compariing the model and the available metamorphic data for the Préalpes Médianes (PM) (KÜBLER et al., 1979; BAUD, 1987, MOSAR, 1988; JABOYEDOFF and THÉLIN, 1996; JABOYEDOFF, 1999, FREY et al., 1999) allows to verify if the metamorphic ages (JABOYEDOFF and COSCA, 1999) agree with basin closure ages (STAMPLI et al., 1998; BAGNOUD et al., 1998; BURKHARD and SOMMARUGA, 1998). The constraints of the model are deduced from cross-section (ESCHER et al., 1997; MOSAR, 1998) and stratigraphic data. The aim of this paper is to discuss the magnitude order of the thermal evolution of the PM, and to estimate the modelling is coherent with other data and interpretation.

Usually the thermal structure of a subduction zone does not agree with a simple model because of a constant cooling effect, but the alpine building was the result of continental collision, which allows the use of a simple model as the one proposed.

2. Geological setting

The Préalpes in Switzerland are made of a sequence of nappes formed mainly by carbonate and flysch series of Triassic to Eocene age (BAUD and SERTFONTAINE, 1980; TRÜMPY, 1980; ESCHER et al., 1997; STAMPFLI et al., 2001). The (PM) are the major unit of the Préalpes; they are the most significant geological element shaping the Préalpes geomorphology (Figs 1 and 2). They are derived from the Sub-Briançonnais and the Briançonnais domains. The principal northwest segment of the PM are Préalpes Médianes Plastiques (PMP), they were detached from the Pontis nappe, lying northwest of the Rhône Valley (Valais), by thrust occurring within the upper Triassic dolomite and limestone (Fig. 3). The PMP are characterized by a true thin-skin tectonic (MOSAR et al., 1996; STAMPFLI et al., 1998) in the frontal part, but the style contains more and more folds involving shearing and flattening down to the SE. The timing of deformation is still poorly constrained. The Préalpes Médiane Rigides (PMR) are probably detached form the Siviez-Mishabel basement nappe. PMR are constituted of an incomplete carbonate series, where most of the shaly Liassic rocks are missing unlike the PMP (Figs 1 and 2). This gives the "rigid" style to those klippen as stretched straight mega-blocks. PMR were detached owing to mid- Triassic evaporates while their undetached equivalent in the internal part is the Barhorn series (SARTORI, 1990), does not contain those levels.

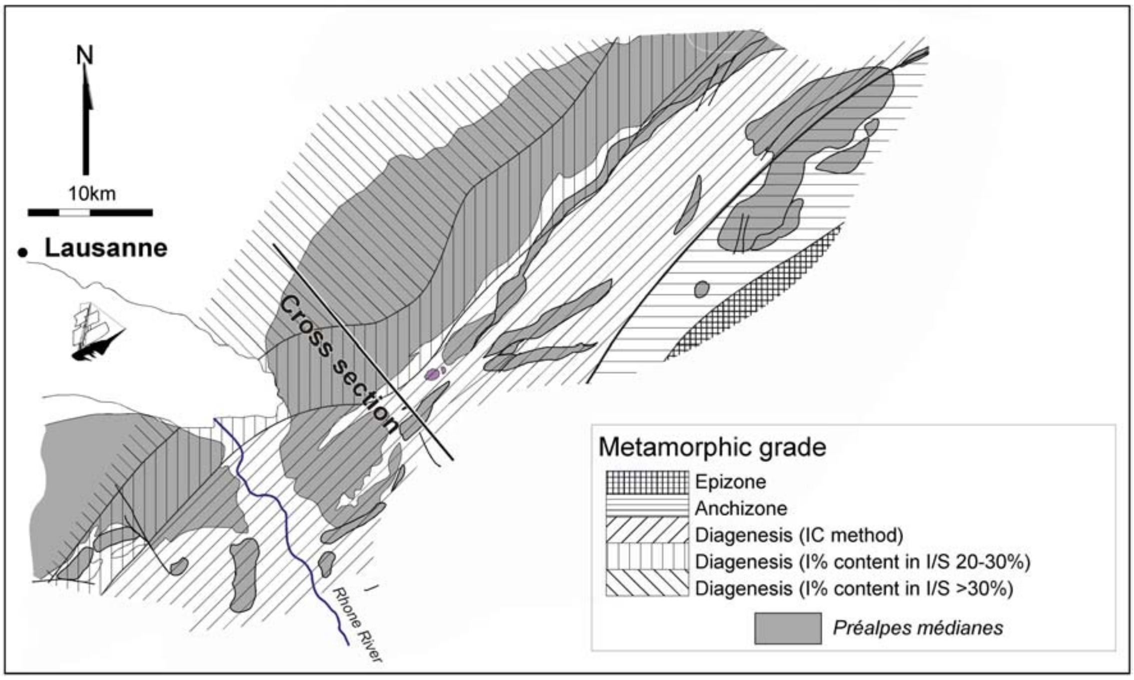

Fig. 1 *Tectonic map and metamorphic zones of the PM (after Jaboyedoff and Cosca, 1999).*

According to the metamorphic data (see below), showing a nearly continuous gradient, the PM can be considered as an almost continuous segment, including some early thrusts (see Fig. 8 in JABOYEDOFF and THÉLIN, 1996).

In the present state the PMP lie over the Ultra-Helvetic (U-H) complex zone (JEANBOURQUIN, et al., 1992) originating from the southern border of the Helvetic domain (LEMPICKA-MÜNCH, 1996) (Fig. 3). The PMP are overlaid by flysch nappes deposited during the Tethys ocean closure. Those nappes are the Sarine nappe, the Dranse nappe and the Simme nappe. The latter originates from the southern margin of the Piémontais domain. The PMR lie on the sub-médiane zone, which is a complex constituted by flysch containing Mesozoic sedimentary blocks and slices. They are overlaid by the Brèche nappe, which contains middle to upper Jurassic brechia, originating from the SE margin of the briançonnais domain and containing Triassic to Paleaocene rocks. The Gets nappe covers all the nappes of the Prealpes. It assumedly originated from the accretionary prism of the Piemont ocean closure (BILL et al., 2001).

All those units belong to a accretionnary prism, consisting of several imbricated thusts. This system of nappes moved on the foreland basin sealing flysch deposits down to NW. The advance is constraint by chrono-stratigraphic data (BURKHARD and SOMMARUGA, 1998; STAMPFLI et al., 1998). The closure Piémont Ocean started during the upper Cretaceous at its SE margin. The NW margin was affected (flexure) by the subduction processes approximately 90 Ma (STAMPFLI et al., 1998). The age of the PM flysch is 47-43 Ma (CARON et al., 1988), but maybe younger 43-37Ma (STAMPLI et al., 1998). This is supported by the sediment ages from the Valaisan domain dated at 34 Ma (BAGNOUD et al., 1998), indicating that at that time the Briançonnais was still a sedimentary basin or had just been completely buried. Most of the displacements to the foreland basin were terminated 22 Ma ago (BURKHARD and SOMMARUGA, 1998). We can conclude that the maximum burial of the PM occurred around 37 Ma, otherwise for older ages the PM would have been subducted more deeply.

It must be noticed that the maximum of burial of the PM corresponds approximately to the slab-break off of the briançonnais terrain (STAMPFLI et al., 1998). This may indicate a change of the collision style of the Alpine chain; the continental crust started thickening (ESCHER and BEAUMONT, 1997).

3. Metamorphic settings

According to illite crystallinity method (FREY, 1987a, 1987b; KÜBLER, 1967, KÜBLER, 1984; KÜBLER and JABOYEDOFF, 2000) and mineral assemblages, the PM were affected by incipient metamorphism from diagenesis deep to anchizone. The grade increases from northwest to the last outcropping rock of this units in southeast (BAUD, 1987, MOSAR, 1988; JABOYEDOFF and THÉLIN, 1996; JABOYEDOFF, 1999, FREY et al.,

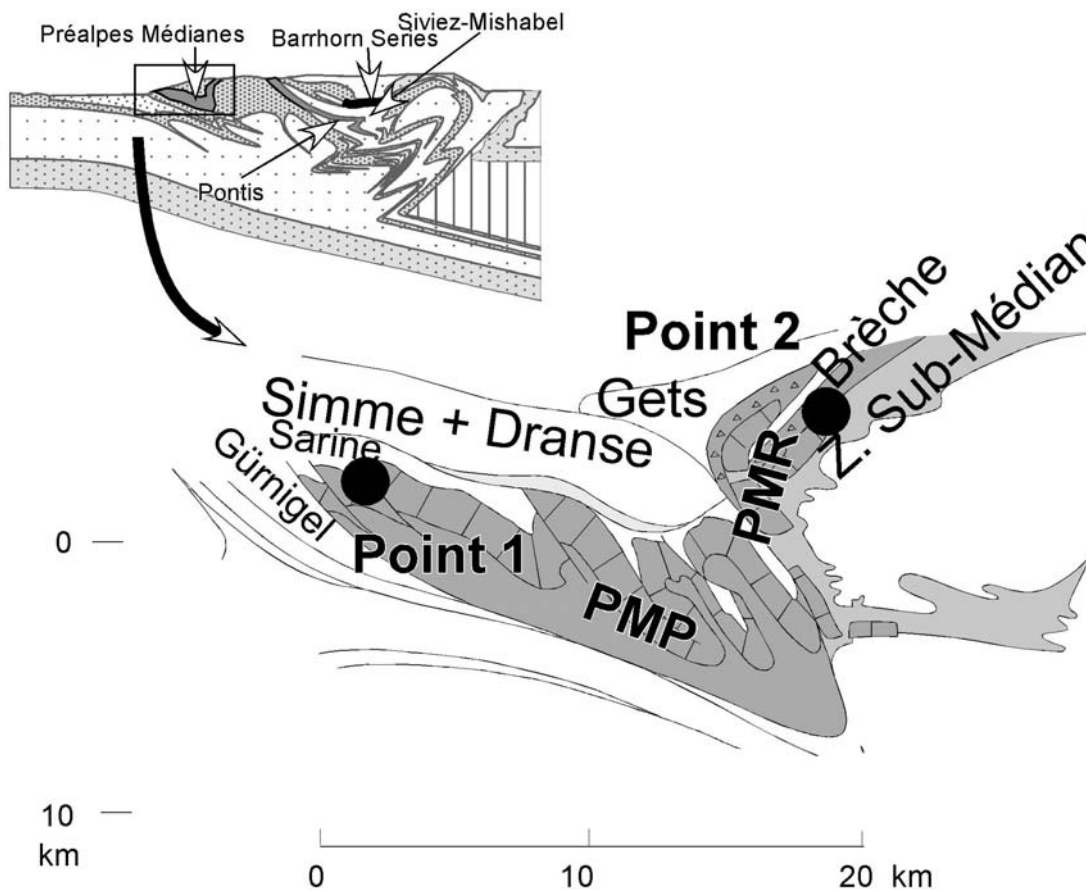

***Fig. 2** Schematic cross section in the Préalpes (after ESCHER and BEAUMONT, 1997/*

1999). Due to unequal erosion level the higher-grade rocks are found only in the NE part of the PM, corresponding to the external part. In this area the metamorphism increases very rapidly down to the southeast. The rest of the series of the Briançonnais that were not detached from the basement (in Valais) reached the green schist facies (epizone). Imbricated trusted units of the PMR like Gummfluh-Rubli Klippes indicate a higher grade of metamorphism for the lower unit. This can be inversed when a klippe thrusts the back of a more external klippe as it can be observed in the Diemtigtal. The PM are thrusted by the "nappe de la Brèche", which displays a lower metamorphic grade (JABOYEDOFF, 1999).

The interstratified minerals illite-smectite (I-S) containing 60-65% illite layers are documented in the frontal part of the PM. I-S with such a illite content generally corresponds to the transition zone from disordered I-S to ordered I-S , in which the I content increases rapidly with increasing burial. POLLASTRO (1993) showed that for slow thermal change, this zone corresponds to approximately 100-110ºC. We will use these conditions and location as point 1 to constraint the model (Fig. 1). This limit is crossed from NNW to SSW in the frontal part and is also suspected vertically near the "Dent de Lyss" in a section cutting the entire PM frontal series just above (JABOYEDOFF, 1999).

The mineral assemblages are in accordance with IC values and show the same distribution, which were synthesized by FREY (1978) and KÜBLER (1984). The appearance of pyrophyllite in anchizonal bauxite, in southern border of PMP, may indicate a reaction temperature of 240-270ºC according to FREY (1987). It agreed well with IC data assuming the temperature scale proposed by FREY (1986) or by JABOYEDOFF and THÉLIN (1996), the SE part of the PM is the second constraint point 2 (Fig. 1).

The age of the metamorphic peak is estimated at 27 ± 13 Ma (2σ) using $^{40}Ar/^{39}Ar$ method and using detrital-neoformed illite ratio (JABOYEDOFF and COSCA, 1999).

The jump of very low metamorphism grade between the stacked of the Préalpes nappes indicated that the metamorphism occurred before the thrusting that putted a higher metamorphosed nappe over a less metamorphosed (Mosar, 1988; JABOYEDOFF, 1999; BILL et al., 2001).

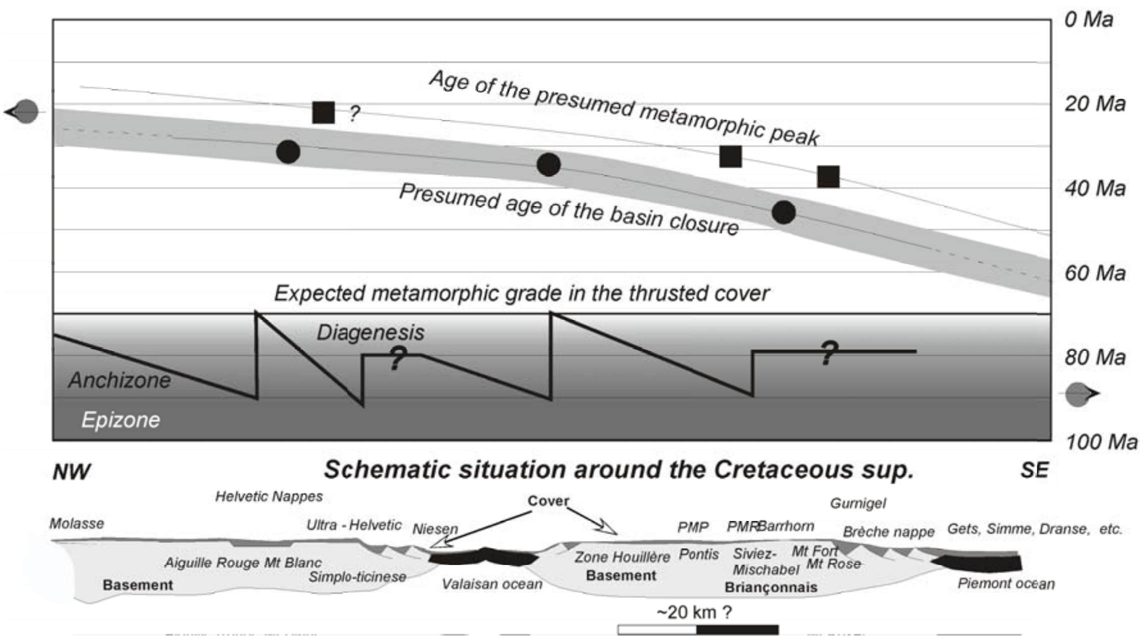

Fig. 3 Paleogeogrphy around the Brianconnais for the Cretaceous sup. Based on available data the ages expected ages of the closure basin and metamorphic ages are display (data from BAGNOUD et al., 1998; BADOUX, 1996; CARRON et al., 1989; FISCHER and VILLA, 1990; JABOYEDOFF and COSCA,, 1999; MARKLEY et al., 1998).

4. Modelling

4.1 Model

Thermal modelling was performed using home-made software in 1D, based on finite difference method (PEACOCK, 1989; RYBACH, 1981, JABOYEDOFF, 2000) following the equation:

$$\frac{\Delta T}{\Delta t} = \alpha(z,t)\frac{\Delta^2 T}{\Delta z^2} + \frac{\Delta T}{\Delta z} v_z(t) + \frac{A(z,t)}{\rho c(z,t)}$$

where Δ is the difference between two consecutive nodes, Δ^2 the difference between two consecutive differences, and (z, t) indicates the dependencies at depth z at time t. z [m] values change with time because of the uplift movements. T [K] is the temperature, Δt [s] the time increment, α [m^2/s] the rock thermal diffusivity, ρ [kg/m^3] the rock density, c [J/(kgºK)] the rock heat capacity, and A(z) [W/m^3] is the rock heat production.

The exhumation history was thus estimated along several vertical profiles. For the numerical modelling the burial is assumed instantaneous, but the timing is constraint by the geological data. In the model the PM are considered as a unique slab thrusted by the more internal nappes: flysch nappes, Brèche and the Gets nappes. Because the PM is mostly outcropping along their entire length, we assumed that the entire PM segment reached the surface approximately synchronously, even if in the present state some internal part are lacking, probably caused by the late helvetic nappes uplift. The exhumation was modelled by a straight segment with an initial angle α with horizontal, decreasing linearly to zero up to present state.

5. Data

The two points (1 and 2) for which temperatures are estimated were located on the cross section of MOSAR (1997) along the layer. The originate distance between the two points is estimated at 30 km. Point 1 (~100ºC) is assumed to be buried at a maximum of 5 km, taking into account the cross section of ESHER et al. (1997). The level used in the simulation to obtain the temperature is located in the PM series at 300 m of its top.

The model assumes a substratum of the nappe made of rock material with granitic thermal characteristics. The PM is made of a 2100 m carbonate rock (2100 m because if an 300 m grid). The rocks thrusted over the PM are considered to be mainly sandstones rocks (flysch). The conductivity is dependent on the temperature, but dependency was not integrated explicitly, the conductivities and diffusivity values are estimated from ROY et al. (1981) from graphics for a temperature of approximately 500ºK (Tab. 1).

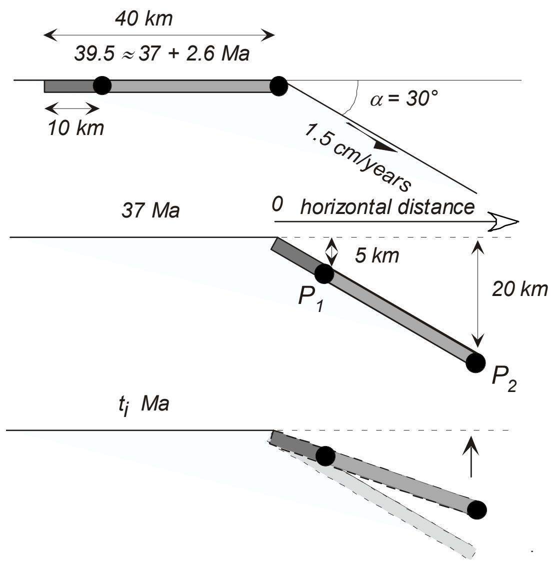

Fig. 4 Model geometry, the PM segment goes up by simple shear.

The initial temperature profile for the substratum was chosen as an equilibrium crust temperature assuming an exponential distribution of heat production (TURCOTTE and SCHUBERT, 1982), the PM are assumed to be in equilibrium with their substratum. In PM and flysch the heat production is constant (Tab. 1). The thrusted flysch pile possesses an equilibrium temperature profile taking into account its constant radiogenic content along its profile.

The youngest suspected age for the PM flysch is 39.5 Ma. The PM slab was probably subducted at 1.5 cm/year (STAMPFLI et al. 1998). The initial angle of the subduction thrust plane "α" was estimated to 30º, iteratively in order to obtain compatible results with the data set along the PM segment. This angle was necessary in order to obtain high enough temperatures. The timing and geometry implies that point 1 initially buried at 5 km was subducted 10 km along the subduction plane, and point 2 reached its maximum burial depth of 20 km after 40 km of translation that corresponds to 2.5 Ma. Thus the maximum burial depth occured approximately around 37 Ma (39.5-2.5 Ma). Note that the model uses 300 m mesh size point then points 1 and 2 were initially buried at respectively at 5400 m and 20400 m.

The surface temperature is fixed at 15ºC, the temperature are computed every 1000 years, and the values are outputted each 1.85 Ma, the mean rock density is fixed at 2750 kg/m^3.

6. Results

The maximum temperatures reached by points 1 and 2 are respectively 127ºC and 300ºC at depths of 4.7 and 14.5 km (Fig. 5a). These values correspond to gradient of 27ºC/km and 21ºC/km at the peak of temperature (Fig. 5b). The ages of those maximums are asynchronous 32 Ma for the point 1 and 26 Ma for the second, while the basin closure age deduced form the assumptions of the model are 39.5 Ma and 38 Ma, which correspond to approximately 13 Ma for point 2 (Fig. 5b). The small thermal inertia of the front of the thrusting may explain the older age of metamorphic peak, this is probably an artefact because for the instantaneous thrusting simulated by the model, a small thickness of material permits a quick heating and then older ages. On the contrary if thrusting is active, the cooling effect will be very efficient and the ages must be younger. Then the ages must be similar to those of the deeper part.

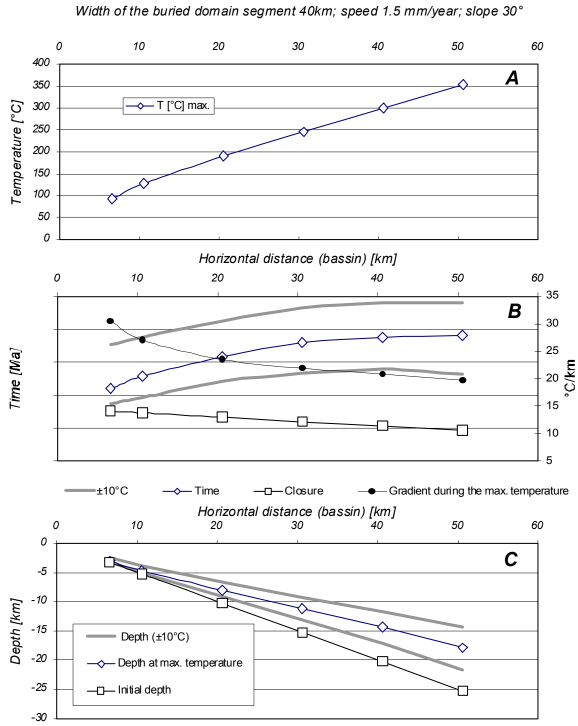

Fig. 5 Results of simulation. (A) Maximum temperature reached in function of the horizontal distance. (B) Basin closure ages, ages of maximum temperature (T_{max}) and corresponding ages range during which $T > T_{max}$- 10ºC. (C) Maximum depth reached and T_{max} depth and depth range for which $T > T_{max}$- 10ºC.

The maximum temperature reached along the PM segment increases quasi linearly with horizontal distance, while the corresponding gradient decreases.

A very troubling fact is the period during which the temperature is only 10ºC less than the peak temperature varies form 8-11 Ma (Fig. 5c). The difference between the maximum burial depth and the temperature peak depth increases also linearly with horizontal distance.

Simulation duration:	37	Ma
Step output time:	1.85	Ma
Time step:	1000	Years
Depth step:	300	m
Density:	2750	kg/m3
Surface temperature:	15	°C

N:	**Thick ness [m]**	**Nb. Points**	**Diffu. [mm²/s]**	**Cond. [W/m°K]**
1	25200	85	0.8	2.2
2	2100	8	0.4	1.2
3	20100	68	0.8	2.0

N	**ρC_p [J/(°K m³)]**	**Qb [mW/m²]**	**Heatprod [μW/m³]**	**Type**
1	$2.75\ 10^6$	30	2.0	
2	$3.00\ 10^6$	0	0.6	
3	$2.00\ 10^6$	30	1.0	

Erosion parameter
Nb erosion periods: 1

Start time [Years]	**Speed erosion [mm/year]**
0	**0.54**

Tab. 1 Values of parameters used in the simulations here for point 2. q_b is heat flux at the bottom of the layer used for calculate the initial temperature profile, for the bottom flux of the model.

7. Discussion

Using this simple model it can be seen that geometrical, metamorphism, and timing are in a good agreement with data. The metamorphic peak is compatible with the 27 Ma deduced from illite dating (JABOYEDOFF and COSCA, 1999). It is also clear from the results that metamorphic ages obtained by mineral dating depend on other parameters than temperature, thus the uncertainty on metamorphic ages is often great, because the peak of temperature last 10 Ma in 10ºC range (Fig. 5b). The development of schistosity or fluid circulation may be then the activator of crystallization.

The modelled temperatures are slightly too high, because a 1D model is used the effect of cooling by underplatting is not integrated (DAVY and GILLET, 1986); as a consequence the temperature must be cooler and probably maximum temperature will be reached later. On the other hand the heating by friction is not integrated, but it is difficult to estimate.

The ages of metamorphism can not be very much younger, because the PM metamorphism must occur before or during their thrusting over the helvetic nappes, because more externally the metamorphism is weaker. Despite those remarks, the favourable model for temperature presented here gives results in agreement with data. To reach the temperatures coming from metamorphic data with a cooling effect (DAVY and GILLET, 1986) like in a subduction zone, the PM would have reached a greater depth than indicates by the present model 20 km (~5.5kb) for the point 2. But it is unlikely because the PM burial is compatible with the ages and temperatures available for Siviez-Miasabel nappe and Barhorn series (MARCKLEY et al., 1998; GOUFFON, 1993; SARTORI, 1990), which underwent greenschist facies. Furthermore, some blueschist assemblages would have been observed, and deformation of the PMR would have been more intense.

This thermal behaviour is probably due to the difference existing between an accretionnary prism and a "continental" accretionnary prism, which occurs when the continental collision begins itself. The shear zones associated with the subduction (ESCHER and BEAUMONT, 1997) may migrate in a deeper level along which the temperature is constant, and then temperature remains constant on the subduction surface or the subduction stopped. Thus thermal cooling is then restricted to the small thrusts, which seems compatible with our results (Fig. 6).

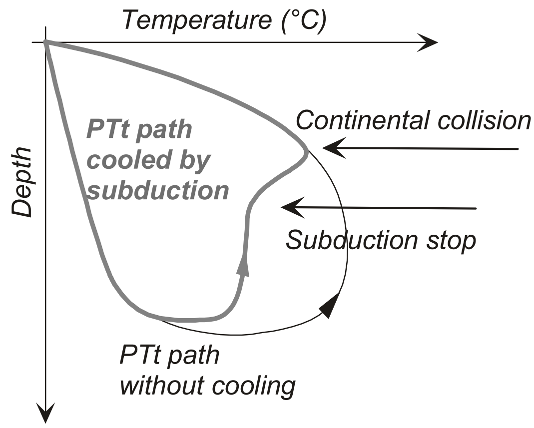

***Fig. 6** Schematic P-T for instantaneous (thin) thrusting and with subduction + continental collision.*

The stop of sedimentation records after 22 Ma in the PM substratum may indicate that it was stopped by the U-H before the arrival of the PM, which could have been affected at that time by the peak of metamorphism.

Ages from the closure of the flyschs sedimentary basins and metamorphic ages indicate a delay of approximately 10 Ma (Fig. 3). It points out a quasi stationary tectono-thermal geometry in the front of the forming nappes like in the model of ESCHER and BEAUMONT (1997) showing successive basement nappes. Another fact is that PM may be metamorphosed during or just after their detachment from their basement.

8. Conclusion

Ages and maximum temperature estimates by simple thermal modelling leads to compatible results. The age of 27 Ma deduced from illites dating is confirmed by the calculated ages of 26 Ma for the maximum temperatures. The use of 1D model and a single geometry does not take into account cooling effect by permanent thrusting activity or the shear heating effect, but their effects are opposite. It indicates that instantaneous thrusting is probably not a bad image of the thermal history of PM. It seems that, taking into account the alpine data and the present results, the cooling effect cannot be very important in a continental collision context. The mechanism may be different from a true subduction zone. Which implies that Préaples nappes are thrusted but not much cooled by underthrusting. The change of thermal behaviour may occur when the subduction becomes a continental collision.

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