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THE STACKING OF THRUST SLICES IN COLLISION ZONES AND ITS THERMAL CONSEQUENCES

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Abstract. The thermal consequences of stacking-up thrust slices in collision zones are investigated using simple one dimensional thermal models. The metamorphic evolution (geotherms and (P,T, time) paths) of a given tectonic unit belonging to a crustal stacking wedge made of more than two units is governed by three effects: cooling and pressure decrease associated with erosion, cooling by the lowest units (screen effect), heating by the upper units(cover effect). It is shown that the efficiency of these effects are dependent on the tectonic evolution of the collision zone. The metamorphic evolutions are very sensitive to the following tectonic parameters: the number of thrusted units involved in thickening, the time delay between each thrust and finally the mode of stacking of the different units (over and understacking). It appears that, for a given depth of burial, the temperature increase during uplift is less important in a crust thickened by three or four units than in the case of two units. The screen effect during understacking is more efficient for a short time delay (∿ 10 Ma) between each thrust.Overstacking leads to higher temperatures before uplift when compared to understacking. It is also shown that the thermal perturbation induced in an intermediate unit of the pile is more efficiently recorded when its thickness is rather small (∿ 10 km). It is shown that, for an erosion-controlled uplift, the shape of the (P,T,t) path depends on the position of the rocks within a given unit and on the unit position within the pile. Finally, the general metamorphic evolutions during crustal thickening (HP-LT metamorphism and subsequent overprint) are discussed in terms of the previously mentioned parameters. In the case of the Western Alps, it appears that the more or less efficient greenschist overprint of the units involved in thickening can be explained by different time intervals between the thrust events.

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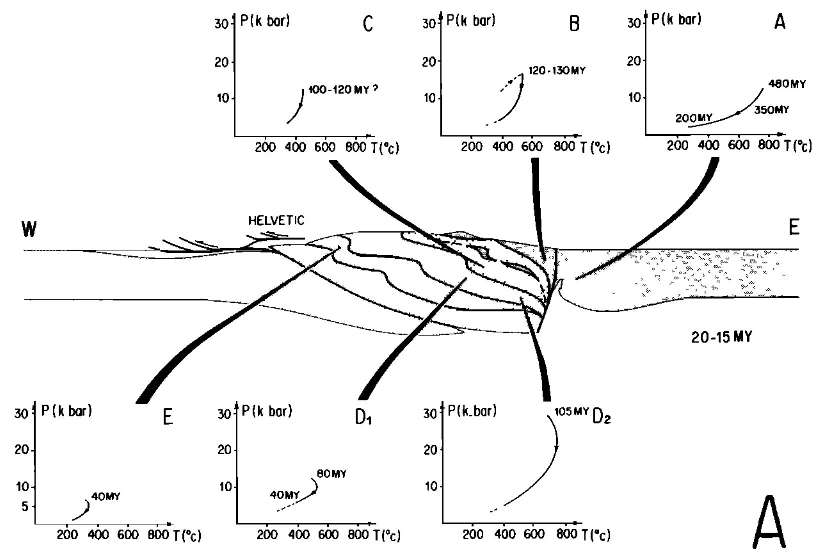
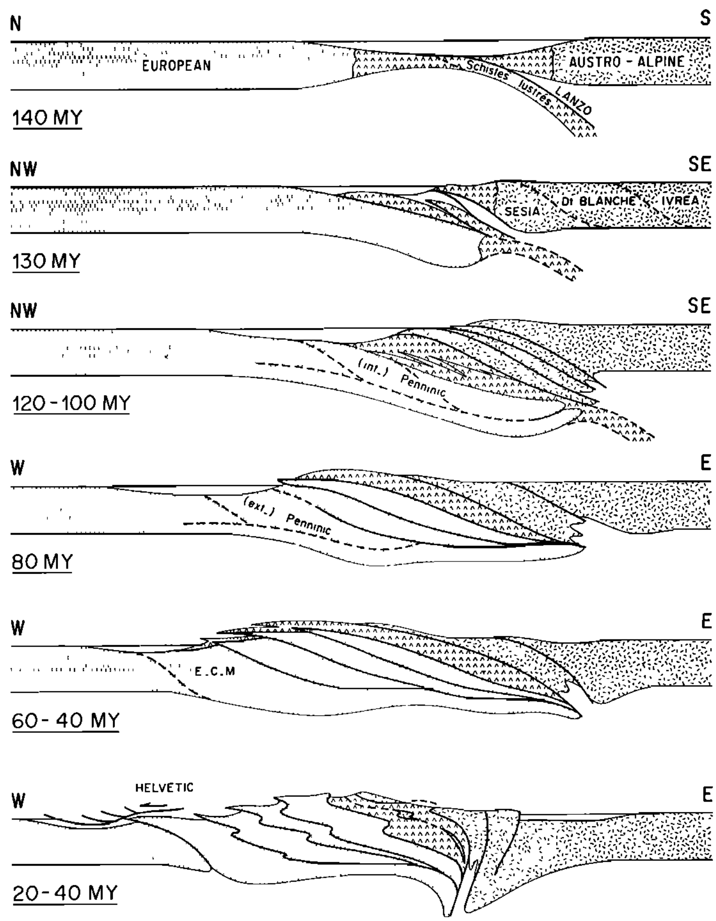
1. INTRODUCTION

Difficulties in understanding the evolution of a given orogenic zone arise from the fact that the velocity field and the associated thermal evolution are not steady. The results of numerous field studies in recent collision zones like the Alps and the Himalayas have emphasized the predominant role of thrusting during crustal thickening. Moreover, collision and crustal thickening appear to occur by progressive stacking-up of continental and oceanic units or slices [Oxburgh, 1972; Mattauer and Tapponnier, 1978; Mattauer 1983; Rubie, 1984; Molnar, 1984; Gillet et al., 1985, 1986; Coward and Butler, 1985].



P(k bar)
T(°c)
C
100-120 MY ?
B
120-130MY
A
480MY
350MY
200MY
W
HELVETIC
E
20-15 MY
E
40MY
D1
80MY
40MY
105MY D2

A



N
S
EUROPEAN
Schistes lustrés
LANZO
AUSTRO - ALPINE
140 MY
NW
SE
SESIA
Dt BLANCHE
IVREA
130 MY
NW
SE
(int.) Penninic
120-100 MY
W
E
(ext.) Penninic
80 MY
W
E
E.C.M
60-40 MY
W
HELVETIC
E
20-40 MY

B

It is now widely recognized that the thermal history is deeply interwoven with the tectonic history and that each process controls the other [Oxburgh and Turcotte, 1974; Oxburgh, 1983].

It has been shown that the complexity of treating the thermal evolution of a collision zone can be overcome by the recognition that there are only a few parameters that control the regional thermal evolution. Models describing heat transfer and the resulting (P,T,t) paths during orogeny have been proposed [Oxburgh and Turcotte, 1974; England and Richardson, 1977; England, 1978; Richardson and England, 1979]. Most of the time they are based on elementary thickening processes: (1) thickening by a single overthrust (intracontinental and ocean-continent subduction or underthrusting or (2) by homogeneous vertical stretching [England and Thompson, 1984].

England and Thompson [1984] have extensively reviewed and refined such an approach and discussed at length the major parameters controlling the thermal profiles and (P,T,t) paths expected in region of thickened crust. They have varied the parameters (heat supply, erosion rate, etc.) over their geologically interesting ranges and concluded on the heat transfer processes during metamorphism on a regional scale. The main assumptions of all the previous models are (1) thickening occurs instantaneously with minor temperature increase and (2) erosion starts at the end or with a certain time delay after the thickening event.

However, as already pointed out, if thickening in collision zones is in fact made of successive thrusting events how can we interpret the thermal measurements (heat flow) or the thermal evolution during decompression (uplift (P,T,time) paths)? Do they give informations on the thermal properties of the crust and the heat flux at the base of the lithosphere or do they express the timing, geometry and kinematics of tectonic events?

The purpose of this paper is to investigate the thermal effects linked to successive thrusting events and to emphasize the strong control of tectonic on the metamorphic history of a collision zone.

2. THICKENING BY CRUSTAL STACKING: TECTONIC PARAMETERS

The reconstruction of the evolution of a continental collision zone like the Alps or the Himalayas assumes underthrusting and piling up of successive crustal wedges (tectonic units) in order to explain their present time structure (Figure 1). The thermal evolution of each tectonic unit is recorded by its (P,T,time) path. On Figure 1 it can be noticed that the (P,T,t) record of the major units within the Western Alps are different from one unit to the other and depends on its structural position within the pile. One of the most striking features of the Western Alps is the fact that both the age and the intensity of metamorphism increase from west to east. Moreover, it seems that the evolution is discontinuous as suggested by the different ages of maximum burial for each unit [Gillet et al., 1986]. According to the available data (Figure 1) [Gillet et al., 1986] it also seems that the different nappes have been emplaced from east to west and that the time delay between each major underthrusting event could have been short (of the order of 10 Ma) or long (of the order of 40-60 Ma) (Figure 1) depending on the stage of the collision history [Gillet et al., 1986]. One can also assume on the basis of outcrop sizes and seismic data [Ménard and Thouvenot, 1984; Allègre et al., 1984] that the thickness of the units

Fig. 1. Evolution of the Western Alps. (a) Present-time idealized cross section of the Western Alps. Five major units and their corresponding (P,T) evolution are distinguished. A, Ivrea zone. B, Sesia-Lanzo zone. C, Oceanic domain. D_1, Internal Penninic zone, Gran Paradiso massif. D_2, Internal Penninic zone, Dora Maira massif. E, External Penninic zone, Briançonnais zone. Available (P,T) evolutions and geochronological data are shown [after Gillet et al., 1986]. (b) Possible kinematic evolution. The present time structure can be explained by the successive stacking-up of crustal and oceanic units. One can notice that the first units are rapidly stacked-up between 130-100 Ma while there exists a delay before the European continent is affected by thrusting.

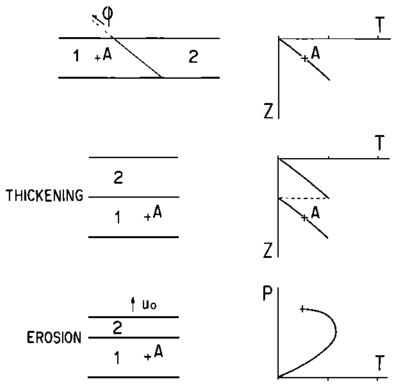


Fig. 2. Thickening by underthrusting. Movement along the thrust fault φ brings instantaneously the "cold" unit 1 at the base of unit 2. Erosion restores the initial thickness. The uplift (P,T,t) path of a point A within unit 1 is presented, notice the temperature increase during uplift.

involved in thickening is rather of the order of 15 to 20 km than 30 to 35 km.

It thus appears that thickening within a collision-zone is controlled by the following tectonic parameters: the number of thrusted units involved in thickening; the structural position within the pile; the time delay between each underthrusting event; the relative position of the successive thrust; the erosion rate.

3. MODEL OF THERMAL EVOLUTION DURING CRUSTAL STACKING

Geological models of collision zones lead us to treat numerically the thermal evolution of a crust thickening by successive underthrusting and subsequent uplift of continental units. Our model will differ from those of previous workers in that we do not consider thickening as resulting from the instantaneous doubling of a crust of normal thickness (Figure 2). Instead, a given amount of thickening (70 km or even more) is achieved by the piling up of more than two nappes.

3.1. Tectonic and Thermal Time Scales

We will assume in all the calculations that heat transfer is predominantly done by conduction in the vertical direction. The time scales linked to the different thermal and tectonic mechanism give us information on their efficiency. For a model of length (thickness) lo, of thermal diffusivity K, and erosion rate u_o we can define two time scales:

$$tc = \frac{lo^2}{K} \quad \text{for conduction}$$

$$te = \frac{lo}{u_o} \quad \text{for erosion}$$

The ratio of the two times defines the Peclet number for the exhumation. England and Thompson [1984] have shown that these time scales are quite similar. Using mean values of the parameters (see appendix) we have $t_c = t_e \sim 30$ Ma.

The time scales associated with the tectonic events can also be roughly estimated. A thrust event has a characteristic time ($t_t = \frac{lo}{v}$, v : convergence rate, lo depth of burial) of the order of 1 Ma if we assume depth greater than 30 km and convergence rates of the order of cm/Y. Such rates are reasonnable if one consider that they respond to convergence rates in active collision belts like the Himalayas. The thrust periodicity (t_p) representing the time delay between each major underthrusting event can be estimated from geological data (in the Alps for instance) to be between 10 to 50 Ma [Gillet et al., 1986].

It follows that nappe emplacement is rapid considering the difference in characteristic times t_c and t_t. This implies that a detailed study of the thermal evolution during a nappe emplacement is difficult to perform. It is thus difficult to tackle the metamorphic prograde path (burial) in terms of models. Though we make calculations assuming an instantaneous stacking of the units we will discuss later the 2D thermal effects related to nappe emplacement. The successive thermal perturbation associated with the thrust periodicity are very important because the time scales t_c, t_e and t_p can be of the same order of magnitude.

3.2. The Numerical Model

To calculate the thermal evolution of a given unit of continental crust, one needs to specify three thermal variables: thermal conductivity, radiogenic heat production and mantle heat flow. In their recent papers, England and Thompson [1984] and Jaupart and Provost [1985] have discussed at length and in details the effects of varying these parameters over ranges of geological interest. Our purpose is not to reinvestigate these effects in the case of a crust thickened by more than two units but rather to emphasize the influence of tectonic on the thermal evolution. Thus we have decided to fix the thermal parameters and following the above authors we have taken mean values of the thermal parameters involved (see Appendix).

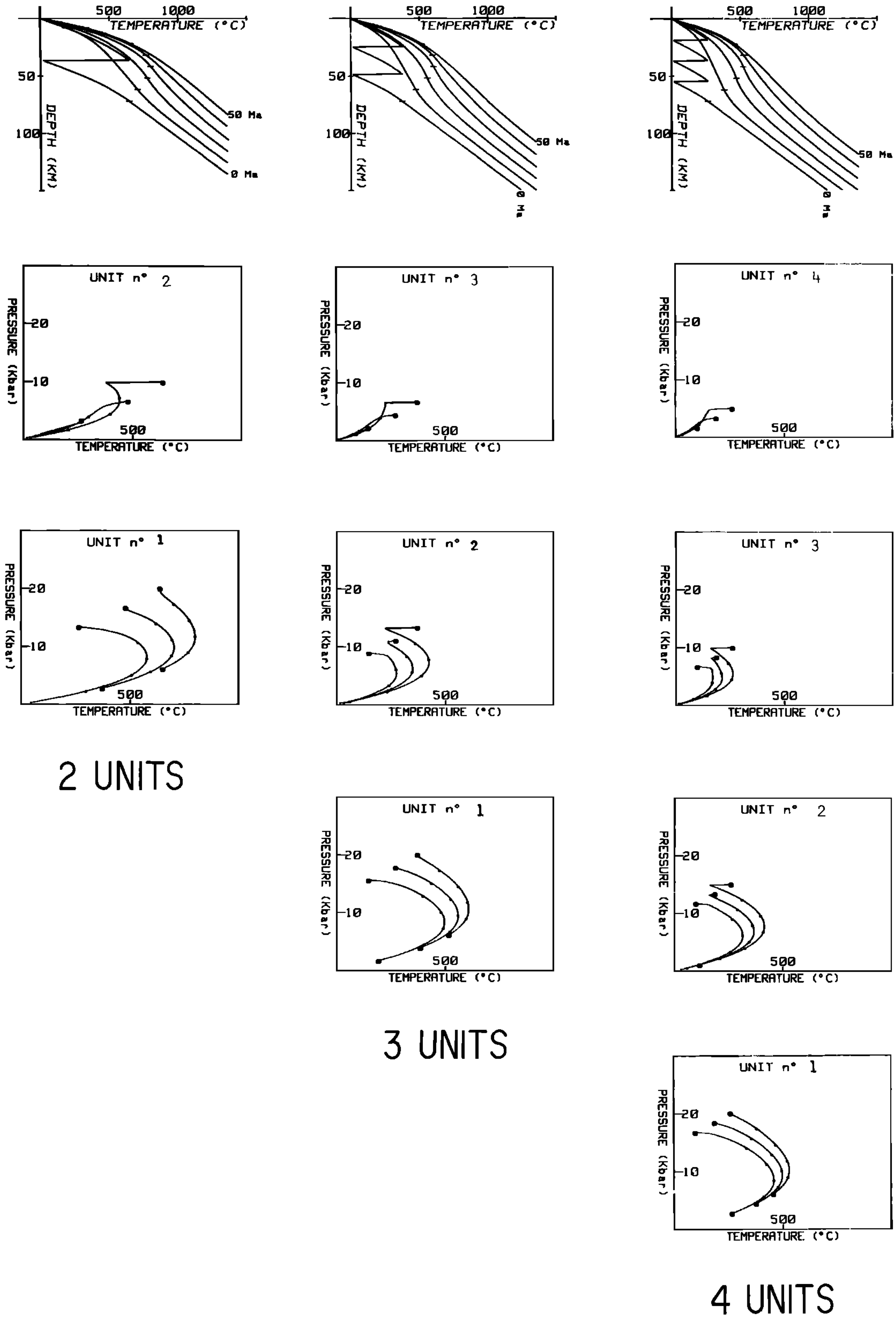
The program (see appendix) allows us to improve the role of the thermal properties of the different units. It also allows us to underthrust different tectonic units successively in time and to vary the duration of underthrusting, the time delay between each underthrusting. The mode of underthrusting can also be varied, namely, the successive units can be emplaced at the top or at the bottom of the previously piled-up units. Some refinement suggested by other authors are also taken into account. The erosion rate can be constant or time dependent and proportional to the topographic height, the inhibition of erosion caused by the eclogite forming reactions (reduction in the buyoancy forces) [Richardson and England, 1979]. All the details concerning the numerical solution of such problems are presented in the appendix.

3.3. Effect of the Number of Thrusted Units

A first set of calculations (Figure 3) presents the thermal evolution of a crust thickened by the instantaneous stacking-up of 2, 3 or 4 units, presenting the same initial temperature distribution and followed by erosion at a rate of 1 mm/yr. The thicknesses of the units are chosen in order to achieve in each case the same amount of thickening (here 72 km for computation simplification). For each case we present the geotherms evolution within the pile and the uplift (P,T,t) paths of rocks buried at different depths, the final geotherm corresponding to an infinite time or a nil erosion rate is the same. The thermal evolution within each stacked-up unit during uplift will then result from the competition between different thermal effects. For instance, the relaxation of the thermal perturbation induced by stacking-up within an intermediate unit of the pile will be governed by the following three effects: cooling by the lowest units (screen effect); cooling and pressure decrease associated with erosion; heating by the upper units (cover effect).

One can first notice that the shape of the (P,T,t) paths depends on the tectonic unit considered. Whatever the case, the upper unit is uplifted with a continuous decrease in temperature. In the case of a stacking of three or four units the (P,T,t) paths of rocks belonging to the second unit present a great variety of shapes depending on the initial depth of the rocks within the unit. Uplift with temperature decreasing or under nearly isothermal conditions is characteristic of the deepest points of the unit, while the upper ones undergo a temperature increase. Such features are due to the existence of a strong screen effect in the lower units and a cover effect in the upper unit. The relative role of the previous effects is inverted for the lowermost units and leads to uplift with temperature increase whatever the position within these units. For a given depth of burial, the temperature increase during uplift (i.e., the maximum temperature reached during uplift) is less important in a crust thickened by three of four units than in the case of two units.

The effect of a delay between the instantaneous thickening and the onset of erosion is presented on figure 4 [Richardson and England, 1979; England and Thompson, 1984]. The (P,T,t) paths of three points buried at depth 9, 27, 45 and 63 km prior to uplift are shown in the case of a pile of 2, 3 or 4 stacked units and uplifted with or without a delay. One can notice that the delay leads to an increase of the maximum temperature before the onset of erosion (isobaric heating) but also of the maximum temperature experienced during uplift. However, the most important feature is that the temperatures endured during uplift by rocks initially buried at the same depth are always lower in the case of a crust thickened by 3 or more units than in the case of a two unit pile (Figure 4). This time delay before erosion starts, appears thus to be a very strong parameter in all thermal models of (P,T,t) path in collision zone. It is clear that such models depends on the thickness of the different units and on their initial geotherm prior to underthrusting. The thermal perturbation induced in an intermediate unit by the upper and lower units are more efficiently recorded when the thickness of the intermediate unit is rather small. The effect is very



500
1000
TEMPERATURE (°C)
50
100
DEPTH (KM)
50 Ma
0 Ma
UNIT n° 2
UNIT n° 3
UNIT n° 4
UNIT n° 1
PRESSURE (Kbar)
20
10
500
TEMPERATURE (°C)
2 UNITS
3 UNITS
4 UNITS

significant between a 35 km thick unit and a 20 or 15 km thick one. Thickening by many superposed units of small thickness (smaller than 35 km) leads to very low geothermal gradients which could account for the unusual low-temperatures-high-pressures metamorphisms and their subsequent preservation during uplift within the intermediate units of the pile (Figure 3).

3.4. Thrust Migration and Thrust Periodicity

We have already pointed out that the emplacement of the different tectonic units responsible for thickening is not instantaneous. The thrusts are spaced in time and are functioning during a certain time interval. A new thrusting event affects the temperature distribution of the previously stacked units and only the new underthrusted unit undergoes a pressure and temperature increase. The units just above the new underthrusted units are in turn cooled and uplifted. It is thus important to know how the pile is built up in space and time. We define two modes of nappe stacking: under and overstacking (Figure 5). The first consists in the thrusting of successive units at the base of the pile and the second one to successive thrusting at the top of the previously stacked units.

Understacking. In this case different thrust planes are successively activated from the internal to the external zones of the thickening zone (Figure 5). Such a mechanism implies that each thrusting event brings a cold slab at the base of the previously piled-up units. However, the thermal evolution (geotherm and (P,T,t) paths) of such a pile will strongly depend on the time delay between each thrust. During this delay the thermal perturbation linked to the previous underthrusting can relax and lead to a temperature increase of the buried rocks. For instance, in the case of a pile made of two units, the rocks belonging to the underthrusted unit will experience their maximum temperature during uplift 10 to 50 Ma after the onset of erosion, depending on erosion rates and thermal parameters. However, the temperature evolution toward the equilibrium geotherm within this two-unit pile can be perturbed by the underthrusting of a new "cold" unit at the bottom of the pile. Figure 6 presents (P,T,t) paths (path 3) of rocks belonging to the lower unit of a stacking-up of two units eroded at a constant rate. One can notice the loop form of the path. Paths 1 and 2 correspond to the uplift paths of the same rocks, but in these cases underthrusting of a third unit 10 or 20 Ma after the onset of erosion has occurred. The thermal perturbation caused by this new event is clearly recorded in the (P,T,t) paths. One can here remark that uplift of the intermediate unit mostly proceeds with a temperature decrease. However, it is clear that the shorter the delay is, the more efficient will be the cooling due to the screen effect. It can be also noticed that the existence of a time

Fig. 3. Effect of the number of thrusted units. Evolution of the geotherms and related uplift (P,T,t) paths for a crust thickened by the instantaneous stacking-up of 2, 3 or 4 units leading to the same amount of thickening. The units present the same initial geotherm but depending upon the level of decoupling the bottom temperature of each unit is different. This leads to different uplift paths. The small dots on the (P,T,t) paths represent time intervals of 10 Ma and the larger dots represent time intervals of 50 Ma. The tick marks on the geotherms represent the successive (P,T) positions of the base of the thickened crust. The erosion rate is 1 mm/Y and the thermal parameters are $A = 1\ \mu.W.m^{-3}$, $Q_\infty = 30$ m $W.m^{-2}$, and conductivity 1 W $m^2 s^{-1}$. For each unit and in the three cases one can follow the uplift (P,T,t) paths of three rocks from different depths within the unit located on a same vertical line before thickening. One can notice that the number and the thickness of the stacked units are important controlling parameters. Thickening by more than two units of small thickness (less than 30 km) leads to lower geothermal gradients and uplift (P,T,t) paths with smaller temperature increase when compared to a stacking of two units of 35 km thickness.

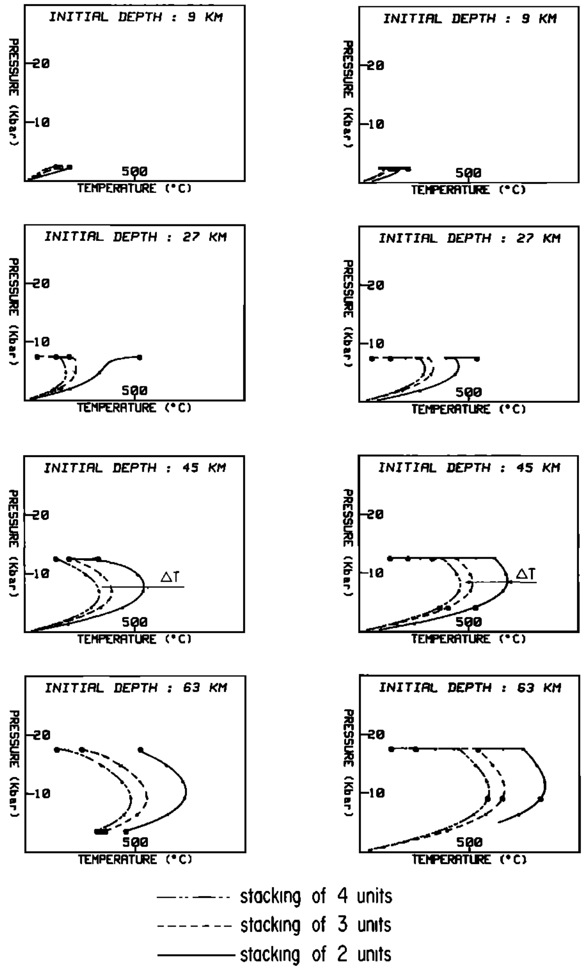


Fig. 4. Effect of a delay before the onset of erosion. Each diagram represents the (P,T,t) paths of rocks buried at a given depth 5, 27, 45, 63 km) in the case of an instantaneous stacking of 2 (solid lines), 3 (dashed lines) or 4 (solid/dashed lines) units. The diagrams on the left correspond to an uplift starting at the end of the thickening event while a delay of 20 Ma exists before uplift on the right figures. The uplift rate is 1 mm/Y and the thermal parameters and symbols are the same as in Figure 3. Two basic effects are to be noticed. The time delay does not affect the temperature difference (ΔT) at a given level during uplift, due to a stacking of 3 or 4 units instead of 2. The delay leads to higher temperatures prior to uplift and to higher maximum temperatures during uplift. Small and large dots represent, respectively, time intervals of 10 and 50 Ma.

delay between each thrust leads to higher temperatures during uplift when compared to the case of an instantaneous stacking-up of the units (compare Figure 7a with Figure 3).

Overstacking. This section concerns the thermal evolution associated with a mechanism of stacking which seems unfrequent or which has not been yet described as such in highly metamorphosed terrains in recent or ancient collision zones. This mechanism of stacking, i.e., overstacking, is for instance active during "décollement tectonics" in duplex systems [Butler, 1983] and consists in the overthrusting of internal unit at the top of the previously stacked units. Analogic scaled models of continental convergence zones have also shown that this mechanism could be active during continental collision [Brun et al., 1985; Davy, 1986]. The overthrusting of a new unit at the top of the pile counteracts the screen effect of the first underthrusted unit in the intermediate unit (Figure 5). Geotherms and (P,T,t) paths corresponding to a delay of 10 Ma between each thrust are presented in Figure 7. One difference at variance with the understacking process, is that maximum pressure is in this case reached after successive increase in pressure interrupted by thermal relaxation and erosion during the time delay between each overthrust. This mechanism accounts for the higher temperatures for the maximum pressure than the one produced by an understacking process. A pile of two units (unit 1 and unit 2) is successively overthrusted by unit 3 and 4. The (P,T,t) paths (Figure 7) show that the maximum pressure of each unit is reached for higher temperatures when compared to the understacking case. The prograde paths (increase in P) of rocks of unit 1 and 2 present an important increase in temperature. Moreover, most of the rocks undergo a temperature increase during uplift whatever their burial depth and reach their temperature maximum at lower depth (compare with the previous case).

3.5. Thermal Perturbation Associated with a Fault: Discussion

The previous calculations were performed with a maximum thermal perturbation. For instance in the case of the understacking mechanism each new thrust brings a temperature of 0°C at the base of the pile,

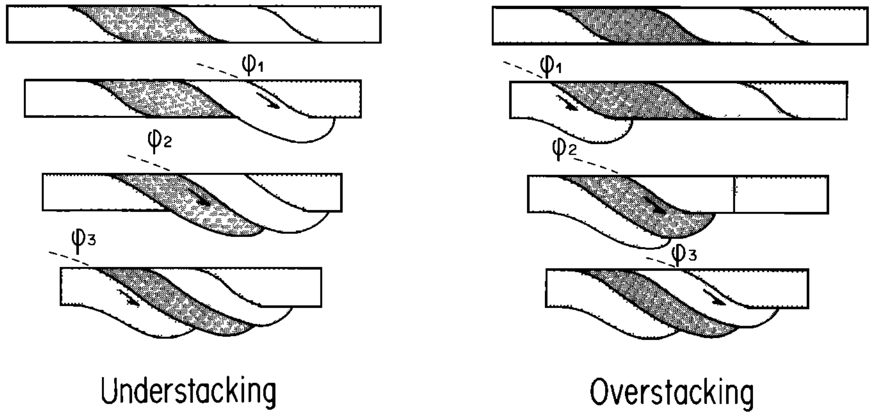


Fig. 5. Relative positions of the successive thrusts. The same final stacking-up can be achieved by different modes. In an understacking fashion each new underthrust brings a new unit at the base of the pile. In an overstacking fashion each new unit is overthrusted on the top of the pile. It must be noticed that the successive thrusts φ_1, φ_2, φ_3 can be more or less spaced in time. The final geometry of the pile is equivalent in the two cases.

corresponding to the ideal case where the upper limit of the underthrusted unit was initially at land surface. It is possible to define a degree of perturbation (Figure 8) by taking the difference in temperature between the base of the pile and the top of the new underthrusted unit. Thermal evolutions corresponding to different degree of perturbation are presented Figure 8. It is clear that the lower the degree of perturbation, the less efficient will be the screen effect. This could happen if the new underthrusted unit was not at the surface before thrusting at the base of the pile (Figure 8). This may be the case of small offsets along a thrust plane. It must also be mentioned that low underthrusting rates [Rubie, 1984] or shear heating during thrusting could perturb the temperature distribution near the thrust zone, but these effects are very difficult to investigate in a quantitative way. In fact, during a non instantaneous nappe emplacement the overthrusting unit is cooled and the underthrusting unit is heated in the vicinity of the thrust plane. These effects are presented Figure 9. Depending on the position along the thrust plane different extreme cases exist. For the deepest points of the thrust plane (A, Figure 9) the upper unit is weakly perturbed, whereas the lower unit has been heated since the beginning of thrusting. Near the surface the effect is inverted (C, Figure 9): the lower unit is weakly perturbed, whereas the uppermost is cooled since the onset of thrusting. The intermediate situation (B, Figure 9) can be considered as a static relaxation of an instantaneous stacking of the units.

These effects like other two or three dimensional effects linked to heat refraction between smoothly deeping stacked units of different thermal diffusivity are probably very important in collision zone [Jaupart et al., 1985; Jaupart and Provost, 1985], but they are not taken into account in our simple models.

4. GEOLOGICAL IMPLICATIONS

The simple calculations of the previous sections have shown that tectonic effects in the mode of thrusting are very important and that geotherms and (P,T,t) paths may be influenced by them. The tectonic evolution of a zone thickening by crustal stacking has to be taken into account in order to interpret all the associated (P,T) signatures. Reciprocally such thermal signatures may be used in the reconstruction of the collision zone histories and constrain geological models [Gillet et al., 1986].

(P,T,t) path shapes. The shape of (P,T,t) path deduced from successive

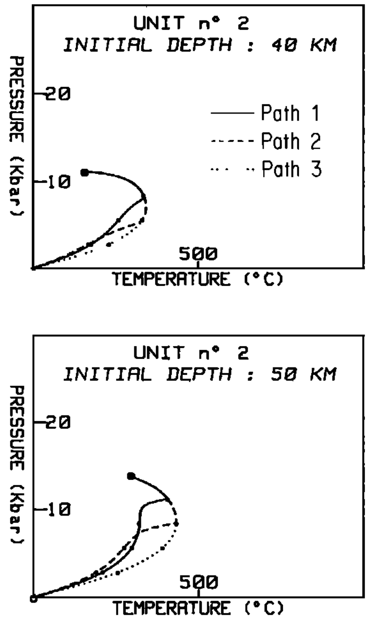


Fig. 6. Effect of a time-delay between each underthrust. A pile of two instantaneously stacked-up units is eroded at a rate of 1 mm/Y. Path 3 corresponds to the uplift of a rock (situated in the middle of the lower unit) without any further underthrusting event. In path 1 and 2 underthrusting of a third unit at time t_1 = 10 Ma or t_2 = 20 Ma, respectively, after the onset of erosion has occurred. The shape of a given (P,T,t) path is sensitive to the tectonic evolution and records the tectonic events. However the screen effect played by the third unit is more efficent for a small time delay (less than 30-40 m.y.).

mineralogical assemblages are often used to constrain possible mechanism of uplift: tectonic or erosion controlled [Carlson and Rosenfeld, 1981; Crawford and Mark, 1982; Spear and Selverstone, 1983; Selverstone et al., 1984; Thompson and England, 1984; Rubie, 1984; Royden and Hodges, 1984; Hodges and Royden, 1984]. For instance, in order to explain the preservation of blueschist terrains or uplift (P,T,t) paths without temperature increase, models based on tectonic exhumation implying very rapid rates of uplift have been proposed [Kienast and Rangin, 1982; Draper and Bone, 1979]. Rubie [1984] has proposed to relate the quasi-isothermal uplift path recorded by the Sesia-Lanzo zone (Figure 1) by the accretion of oceanic material which maintains at the base of this unit during uplift a constant temperature while subduction occurs. This alternative model is very sensitive to parameters like the duration of subduction, the temperature at the base of the crust which are difficult to bracket from geological data. Nevertheless, the basic physical mechanism, appears to be the same as the screen effect invoked in this paper. In some other cases the changes of shape occurring within a same uplift (P,T,t) path have been explained by successive variations in the erosion rate [Dempster, 1985]. Our numerical experiments show that the successive tectonic events occuring during the formation of a crustal stacking wedge can lead, for a steady erosion uplift at the same rate, to a great variety of uplift (P,T,t) paths (with or without temperature increase) depending on the position of the studied rocks within the units and the units position within the pile. The successive underthrusting events affect the (P,T,t) path shape of the overlying units. It seems thus clear that the construction and especially the interpretation of (P,T,t) paths within collision zone cannot be done in the absence of a careful study of the tectonic setting [Caron, 1983]. Moreover, the recorded (P,T,t) paths can be used to constrain the tectonic setting during uplift. Goffé and Velde [1984] and B. Goffé [unpublished manuscript, 1985], have related the contrasted uplift histories (P,T,t) paths of different portions of the same unit of the Western Alps (Briançonnais zone, Figure 1) metamorphosed in the blueschist facies, to differences in the tectonic events accompanying uplift. For instance an uplift path beginning by a decrease in temperature at constant pressure and followed by both pressure and temperature decrease has been interpreted by the underthrusting of a colder unit. At variance with this part of the unit other parts have been uplifted with a temperature increase, precluding the occurrence of a thrusting event.

We have already pointed out that overstacking is a mechanism which is not often documented in crustal metamorphic terrains. However, there are hints that this mechanism may be active during continental collision. In fact, overstacking can be detected by careful petrographic investigations and methods which allow the obtention of continuous (P,T) path segments rather than successive separated (P,T) points. The use of garnet zoning appears to be a challenging method.

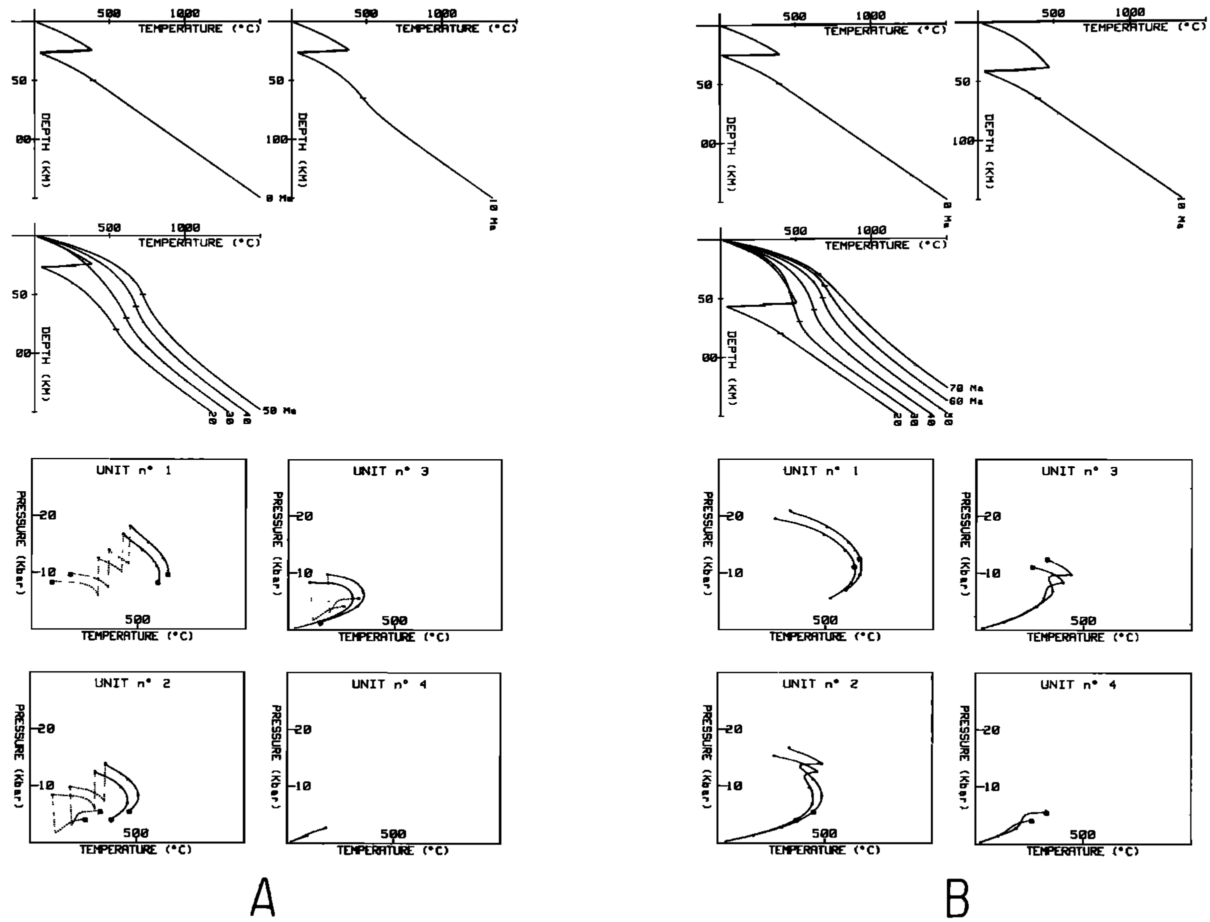


Fig. 7. Geotherms and (P,T,t) paths related to the two tectonic evolutions of Figure 5. (a) Overstacking. In this case the prograde path is different and leads to higher temperatures for the maximum experienced pressures. Notice also that whatever the position within the pile (at the exception of the upper unit) uplift path has a loop shape (i.e., uplift proceeds with temperature increase). (b) Understacking. There exists a delay of 10 MY between each thrust. φ_1, φ_2 and φ_3 during which the previously stacked units are uplifted at a rate of 1 mm/Y. The underthrusting of a new unit is instantaneous. Notice that the existence of a delay leads to higher temperatures during the prograde path when compared to the case of instantaneous stacking-up (Figures 3 and 4). Unit 1 and 2 present (P,T,t) paths with temperature decrease during decompression. The (P,T,t) path of units 3 shows a quasi-isothermal uplift during half the uplift history while unit 4 undergoes a large temperature increase during uplift. Same symbols and thermal parameters as in Figures 3 and 4. For each unit the uplift (P,T,t) paths of two rocks from different depths prior to thickening are drawn.

Selverstone et al. [1984] and Selverstone [1985] have observed reversals in the (P,T) paths determined from garnet zoning in some units of the Tauern Window (Eastern Alps). These reversals consists in brief increases in pressure (~ 2 kbar) at constant temperature during uplift. They have related such increases to the overstacking of more internal units on the considered units [see Figure 8 in Selverstone, 1985]. A similar mechanism may be proposed in the earliest stages of collision in the Western Alps [Gillet et al., 1986] (see following section).

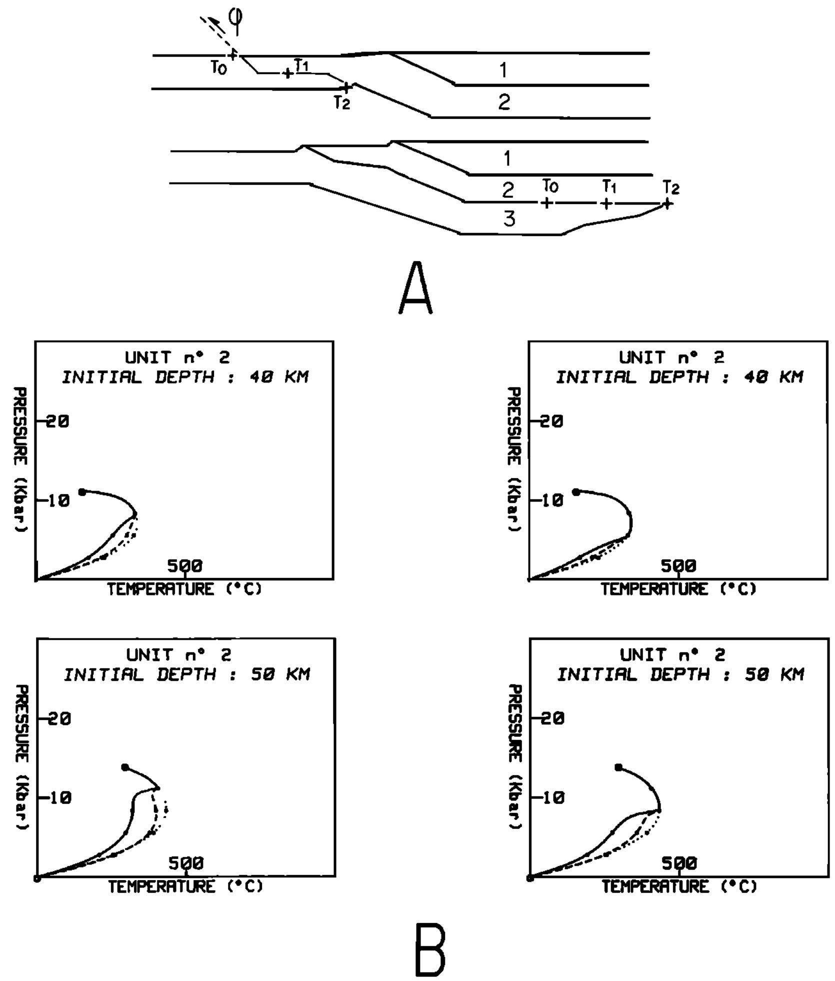


Fig. 8. Effect of the temperature at the top of the underthrusted unit. (a) An initial stacking up of two units (1 and 2) is eroded at a constant rate (1 mm/Y). Following the initial underthrusting a third unit (3) is underthrusted 10 or 20 Ma later. Due to the geometry of the thrust itself, temperature at the top of unit 3 varies and unit 2 depending on the position will see different temperatures at it base ($T_2 > T_1 > T_0$). (b) Calculated (P,T,t) paths for the uplift of samples belonging to unit 2 and buried at depth 40 and 50 km. The dotted paths correspond to and uplift without underthrusting of unit 3. The full line paths correspond to a temperature $T_0 = 0°$ at the top of unit 3 and the dashed paths to a temperature of T_1 (= half the temperature at the base of unit three before thrusting). Same symbols and thermal parameters as in Figure 3.

Metamorphic evolutions. Some general problems concerning the acquisition and preservation or overprint of a kind of metamorphism in collision zones can be tackled in the framework of the previous models. The calculations carried out by England and Thompson [1984] show that HP-LT metamorphism (blueschist to eclogite metamorphism) by doubling the crust thickness (two units 35 km thick) is experienced in the lower crust (the lower unit) in the earliest stages whatever the heat supply. However, the preservation of such metamorphism depends on the existence of high thermal conductivities, high erosion rates [Draper and Bone, 1979] or the persistence of low geothermal gradients. We have shown in this paper, using mean values of all the parameters such as thermal conductivities and erosion rates, that low geothermal gradients can be maintained in the first underthrusted units

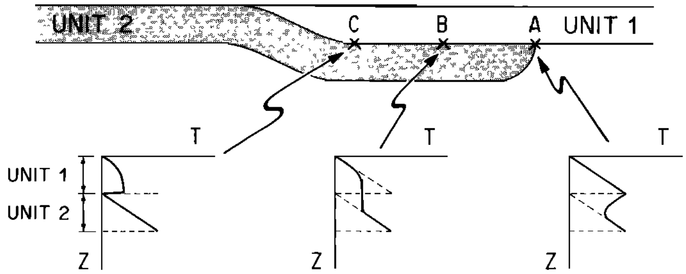


Fig. 9. Thermal effects of a non instantaneous thrusting. A, B and C are points along the thrust plane. The geotherms along a vertical line passing through this points are presented. Dashed lines are the geotherms prior to thrusting. Full lines represent the geotherms for the present situation (see text for further comments).

if during their uplift a new "cold" unit playing the role of a thermal screen is underthrusted under them. The effect is enhanced for short time delay between the thrusts and for thin unit ($\sim$ 15 km). In the western Alps for instance there are lines of evidence for a rapid stacking-up of the first four units (Figure 1) [Gillet et al., 1986]. The (P,T,t) path of the intermediate units correspond to a decompression with temperature decrease (Sesia-Lanzo zone) leading to a very efficient preservation of the eclogitic assemblages. However, there exists a time delay of 40 MY before the underthrusting of a new cold unit at the base of this pile allowing a more efficient thermal reequilibration within the lowest unit of the pile (Grand Paradis massif-Dora Maira massif) during uplift accounting for an uplift (P,T,t) path under nearly isothermal conditions or at least with a small temperature increase. The HP-LT assemblages are intensively retromorphosed in this unit. The difference in metamorphic record of these two units can thus be simply explained by a difference in the time delay between thrust events.

Overstacking and understacking during continental collision. Overstacking seems to be operative as shown for instance by Selverstone [1985], during tectonic imbrications following the collision between continents. However, the overstacking process established by Selverstone [1985] on the basis of petrological records concerns probably rather small units. Our simple numerical models have shown that over and understacking events have not the same thermal signatures and it is thus important to know if large scale overstacking can occur during continental collision. If we consider the existing models of the alpine chain and especially of the Western Alps we can see that both under and overstacking processes are operative at different time of the collisional history. In all these models [Mattauer and Tapponnier, 1978; Caby et al., 1978; Gillet et al., 1986], the onset of collision is preceeded by obduction of oceanic crust onto the european margin (Figure 1). Following this first tectonic event, the emplacement of the austro-alpine units (African units) on the oceanic crust previously emplaced can be considered as an overstacking process (Figure 1). The further thrusting events affecting only the european crust from the internal to the external zones are typically understacking events. The tectonic history for the alpine collision in Northern Pakistan implies also overstacking at early stages of collision [Tahirkheli et al., 1979]. The fact that overstacking is operative at the onset of collision and affects only units belonging to the continent situated above the subduction plane must be related to specific boundary conditions or to preexisting discontinuities (i.e., weakened zones) within the overriding continent. Such discontinuities can be for instance thinned zones induced by back-arc spreading.

The position of the successive thrusts (Figure 5) appears also to be an important parameter especially in the prograde history. We have shown that in the case of thickening by overstacking the high pressures in each unit are reached for higher temperatures when compared to an understacking process (Figure 7). In the Western Alps, units like the Dora Maira massif (Figure 1) have undergone unusual high pressures (30 kbar) [Chopin, 1984; Gillet et al., 1984] which have been reached for temperatures far too high (750°C) to be explained by understacking of successive units. It seems that the successive overthrusting of this unit by more internal units accounts in a better manner for the observed (P,T) conditions of the maximum metamorphism (Figure 1). It is not necessary to invoke a time delay between the onset of erosion [Richardson and England, 1979] or low understhrusting rates [Rubie, 1984] to account for the temperature reached during burial. Experimental models of collision zones using analog materials [Brun et al., 1985; Davy, 1986] have shown that during continental collision some units can be stacked by overstacking. We have already pointed out (Figure 7) that the metamorphic evolution of the units are different. Overstacking appears thus to be a more efficient stacking process than understacking for explaining melting of the crust during uplift of a thickened zone.

Unit thickness and decoupling zone. The thermal evolution within a pile-up of different units is dependent on the thickness of the units [Figure 3]. In particular the thermal perturbations induced in an intermediate unit of the pile are more efficiently recorded when its thickness is rather small (a few kilometers). The size of the unit is controlled by the decoupling zones activated during collision or subduction in both cover and basement rocks. We have recently suggested [Gillet et al., 1986], on the basis of precollisional metamorphic assemblages, that different decoupling levels are activated in the basement of both european and african continents. It appears that the Moho and the granulite-amphibolite limits are largely reactivated during the alpine orogeny (Figure 1). This puts limits, between 30 and 15 km for the thickness of the crustal units superposed during thickening. The oceanic units obducted at the earlier stage of collision are in fact thinner and probably never exceed 10 km in thickness on the basis of the known ophiolitic sequences nowadays exposed in collision zones.

The thickness of the cover units is more difficult to estimate. According to the observations in undeformed oceanic margins the mean thickness of the sediment cover on oceanic crust is of the order of 1-2 km and 5 to 10 km on continental crust.

Most of our models were computed for units more than 10 km thick and reflect the thermal evolutions of large basement units. The behaviour of the sedimentary cover is likely to be different. During continental collision or subduction, tectonic thickening of sedimentary material deposed on oceanic or intermediate crust can lead to apparent thicknesses of cover series of the order of 10 to 20 km. This is the case in accretionary prisms and perhaps was the case in the "schistes lustrés" units in the Western Alps. This rather important thickeness results from the successive superpositions of thin cover units which probably accounts for their blueschist to eclogite metamorphism and their uplift under rather cold conditions implying a good preservation of the HP-LT assemblages.

5. CONCLUSION

Simple thermal models taking into account the tectonic evolution of a collision zone have allowed us to emphasize the following points:

1. Geotherms and (P,T,t) paths in collision zone where thickening occurs by stacking-up of crustal units are very sensitive to tectonic parameters such as the number and the thickness of thrusted units, the time delay between each thrust, the position of the successive thrusts.
2. Major metamorphic evolutions of units involved in the stacking-up can be explained by differences in the values of these parameters (example of Western Alps). The preservation of high-pressure low-temperature assemblages appears to be best explained in intermediate units of a crustal pile when the time delay between the thrusts is small and when the thickness of the units is small.
3. The use of the shape of (P,T) or (P,T,t) paths cannot be used as an uplift mechanism indicator if the position of the studied rocks within the unit and the unit position within the pile are not specified.

Finally, it seems that tectonic effects are important and the associated thermal effects strongly reflect them. Thus, it becomes difficult to derive values of heat transfer processes within collision zones if the tectonic setting and evolution are not taking into account. Our models are applicable to present time or recent collision zones like the Alps, the Himalayas, but also to older collision belts like the Hercynian chain. The geological implications of our computations have focussed on the metamorphic evolutions of the major tectonic units involved during continental collision. Nevertheless, the

TABLE A1. Thermal Parameters used in calculations

	Conductivity, $W\ m^{-1}\ K^{-1}$	Diffusivity, $m^2\ W\ s^{-1}$	Cp, $J\ K^{-1}\ m^{-3}$	Heat Generation, $W\ m^{-3}$
Crust	2.5	1	$2.5\ 10^6$	0.6
Mantle	2.5	1	$2.5\ 10^6$	0

Mantle flux q_m = 30 m W m^{-2}.

model is also applicable to zones of complex tectonic imbrications where the thickness of the units is very small (∿ 2 km) as for example accretionary prism or thin-skinned tectonic zones.

APPENDIX

All the thermal problems were solved using a one-dimensional (vertical) time dependent heat conduction in a coordinate system moving with the medium:

$$\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial t^2} + \frac{Ao}{\rho Cp}$$

where K the thermal diffusivity is taken to be constant. Cp, ρ and Ao are, respectively, the specific heat, density and heat production per unit volume of the medium. Ao is taken constant in each crustal unit.

Equation (1) is solved by the finite difference method with discrete values of temperature

$$T^n = T\ (z,t) \qquad z = m.\ \Delta z \qquad t = n.\ \Delta t$$

and using the approached equation:

$$T^{n+1}_m = M(T^n_{m+1} + T^n_{m-1}) + (1 - 2M)\ T^n_m + \frac{Ao}{\rho Cp}\Delta t$$

Such a scheme is stable for M < 1/2.

In order to solve this linear set of equations the following boundary conditions are used. The heat flux at the base of the lithosphere (∿ 100 km under the crust) is constant. This condition, discussed by England and Thompson, implies that mantle convection is vigorous enough to be unperturbed by thickening of the crust.

The surface of erosion has a constant temperature of 273K. If Z(t) is the depth of this surface at time t = n Δt we define m_o as

$$(m_o - 1)\ .\ \Delta Z \leq Z(t) \leq m_o\ .\ \Delta Z$$

Assuming that temperature is a linear function of depth, we impose between $(m_o - 1)\Delta Z$ and $m_o\ \Delta Z\ T^n_{m_o - 1}$ as

$$T^n_{m_o-1} = T^n_{m_o} \frac{Z(t) - (m_o-1)\ \Delta Z}{Z(t) - m_o\ \Delta z}$$

This scheme has been successfully (at 2%) tested for constant denudation rates and heat production against the suitable algebraic solution given by Carslaw and Jaeger [1959, p. 388].

At the interfaces between the successive underthrusted units we impose heat flux continuity, even for units of different thermal properties.

Following Albarede [1976], England and Thompson [1984] and Jaupart and Provost [1985], all the calculations were performed using the mean values given in Table A1.

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