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Late-orogenic heating during exhumation: Alpine PTt trajectories and thermomechanical models

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Abstract

During the Alpine orogeny, the Penninic zone of the Alps was affected by Eoalpine high-pressure metamorphism. In the central and western Alps, this was followed by Lepontine medium-pressure, high-temperature metamorphism during exhumation. We compare the pressure–temperature–time (PTt) trajectories established in two key areas in the central and western Alps with 2-D numerical models of two possible causes of Lepontine metamorphism: (1) detachment or breakoff of a subducting slab, and (2) the presence of a wedge of accreted radiogenic material. Numerical models show that both mechanisms are capable of producing significant heating during orogeny. Heating by slab detachment is fast and transient (more than 100°C in up to 10 million years, depending on the location), whereas radiogenic heating requires time spans of the order of tens of millions of years and cessation of the subduction process. The combination of PTt trajectories and synthetic PT paths deduced from our thermomechanical modelling results suggests that the metamorphism observed in the central Alps has not been caused by radiogenic heating alone. Slab breakoff, on the other hand, seems a viable mechanism to account for the documented rise in metamorphic temperatures during exhumation. In view of the time constraints posed by the geological data, and acknowledging the effects of large-scale block rotations and out-of-section transport, slab detachment is also a more likely mechanism to have provided sufficient heat to cause re-heating in the western Alps.

Keywords: Alps; Gran Paradiso; Lepontine; metamorphism; thermomechanical model; slab detachment

1. Introduction

The fundamental geodynamic processes underlying the metamorphic evolution of crustal rocks in orogenic belts have long been studied. Since the advent of plate tectonics, high-pressure, low-temperature (HP–LT) metamorphism is interpreted as the result of subduction processes and related crustal thickening. However, in convergent orogens Barrovian medium-pressure, high-temperature (MP–HT) or low-pressure, high-temperature (LP–HT) metamorphism is less readily explained in terms of unambiguously identifiable heat sources.

The Alps are a relatively narrow, arcuate

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mountain belt formed in response to subduction of the Piemonte–Ligurian branch of the Neotethys and subsequent collision of Adria (an African promontory) with the Eurasian continent. During this process of subduction and eventual collision, substantial volumes of continental rocks presently exposed in the internal zones of the Alps underwent HP metamorphism. In previous studies we, and others, have shown that in parts of the Alps peak pressure metamorphism was followed by a stage of high-temperature, medium-pressure metamorphism [1–4], accompanied by magmatism along the Periadriatic lineament (e.g. [5]). These two stages in Alpine metamorphism, classically referred to as the Eoalpine (HP–LT) metamorphism and the subsequent Lepontine (MP–HT) overprint, call for a geodynamic context explaining the increased temperatures during exhumation of the high-pressure rocks.

Two fundamentally different candidate mechanisms were proposed to explain a stage of re-heating during the exhumation of high-pressure metamorphic rocks: (1) slab detachment [6, 7, see also 8, 9], and (2) the development of a wedge of tectonically accreted radiogenic material (TARM) above the subduction zone [10]. We use 2-D thermomechanical models to investigate the thermal consequences of these geodynamic scenarios, which, at first inspection, concur optimally with the wealth of geological data from the Alps, including continental lithosphere subduction.

This study addresses whether significant heating of rocks during their exhumation can be caused by either of the two mechanisms, and if so, on what time scale and under which circumstances we may expect a thermal signal of the kind observed in the Penninic Alps. We compare the numerical results with our observations on the metamorphic evolution of rocks exposed in two key areas described below. Furthermore, we address the relevance of the models for the study areas, and their significance for the geodynamics of the Alps.

Though focussed on the Lepontine metamorphism in the Alps, the results of this study are potentially relevant to explain the metamorphic evolution of other orogenic systems. A clear candidate seems the Variscan belt of western Europe, showing evidence of considerable heating during low-pressure, high-temperature metamorphism near the end of the Variscan cycle, such as the andalusite–cordierite–sillimanite facies series in the Axial Zone of the Pyrenees [11]. Removal of cold lithosphere and ascent of hot asthenosphere to near-crustal levels have been suggested to have affected the Variscan belt during the later stages of that orogenic cycle [12,13].

2. Setting and PTt trajectories of two Alpine eclogite localities

Two areas in the internal Penninic zone of the Alps were selected for a detailed study of their metamorphic histories (Fig. 1). These areas are located in the Lepontine gneisses near Alpe Arami in the central Alps and in the Gran Paradiso basement of the western Alps. They were chosen about 150 km apart, measured along the Alpine arc, in order to obtain orogen-scale insight into similarities and differences in the metamorphic evolutions of the rocks involved. A summary of the pressure–temperature–time (PTt) trajectories of the two areas is given below, and they are documented in detail elsewhere [2,4].

2.1. Lepontine gneisses, central Alps

We have studied the Lepontine gneisses near Alpe Arami in the Swiss central Alps, about ten kilometres north of the main boundary between the European and Adriatic realm, i.e. the Insubric Line (Fig. 1). They are thought to have been derived from the southern margin of the Eurasian continent (e.g. [14]). Subduction of the Piemonte–Ligurian ocean underneath Adria started between 110 and 71 Ma [15] and lasted until 65 Ma. The total convergence between Adria and Europe in that time span is estimated at some 300 km [15,16], followed by subduction of the Briançonnais micro-continent between 65 and 56 Ma and the Valais oceanic basin between 56 and 50 Ma [16]. The European continental margin subducted underneath Adria from about 50 Ma onwards, while convergence proceeded at an estimated rate of 1.0–1.5 cm/yr [17]. Lithospheric thickening

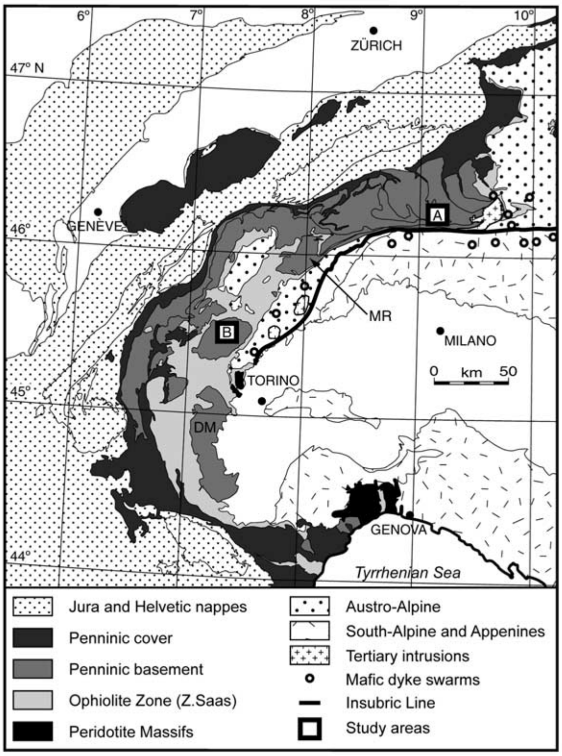

Fig. 1. Map indicating the two areas considered, and main tectonic units and structures in the Alps. Key: A, Lepontine gneisses; B, Gran Paradiso; DM, Dora Maira; MR, Monte Rosa. Modified after the structural model of Italy [47]; magmatic units after Von Blanckenburg et al. [18].

may have accommodated part of the convergence after continental collision, but HP metamorphism of continental material indicates that continental subduction proceeded to considerable depths. An episode of magmatism occurred along the Insubric Line in the central and eastern Alps between 42 and 25 million years ago (Fig. 1), and some of the magmas have geochemical signatures indicating interaction with mantle-derived melts [18].

Our study of the Lepontine gneisses near Alpe Arami indicates that these rocks underwent HP metamorphism at about 870°C and 1.9 GPa [2], equivalent to a burial depth around 70 km (Fig. 2). The age of the HP metamorphism has been estimated at 37.5 ± 2.2 Ma [19]. The rocks cooled to about 630°C during fast initial exhumation (at average rates in excess of 7 mm/yr) and were then re-heated by about 110°C to a peak temperature of 740°C at about 0.6 GPa. The age of this re-heating is inferred to be 32.4 Ma [20]. In summary, continental collision at or shortly after 50 Ma was followed by a stage of re-heating before 32 Ma ago, in which rocks that had undergone HP metamorphism around 37.5 Ma were re-heated by about 110°C at a depth of about 20 km (Fig. 2). After re-heating, the rocks were exhumed at an average rate of about 0.8 mm/yr.

2.2. Gran Paradiso, western Alps

Three 10-km scale basement massifs form the core of the Penninic zone of the western Alps: the Monte Rosa, Gran Paradiso and Dora Maira massifs (Fig. 1). These massifs, also referred to as the Internal Penninic Nappes, are made up of metasediments and orthogneisses and are thought to represent basement fragments of the Briançonnais ribbon continent, located palaeogeographically in between the Piemonte–Ligurian and Valais oceanic basins (e.g. [21]).

The Briançonnais ribbon continent was subducted underneath Adria from about 65 Ma at a rate of about 1 cm/yr [22]. The Gran Paradiso massif underwent HP metamorphism at about 525°C and 1.4 GPa [4], equivalent to a depth of about 50 km (Fig. 2). The age of this HP metamorphism is inferred to be 43 Ma from Rb-Sr white mica dating (Meffan-Main, pers. commun.). The rocks cooled during initial exhumation, and were subsequently re-heated by about 50°C to peak temperatures around 550°C at a pressure of 0.6 GPa, equivalent to a depth of some 20 km. The timing of this re-heating is likely before 34 Ma, which is the Rb–Sr white mica age obtained from a shear zone in the overlying unit, reflecting conditions of 350–500°C and 4–6 kbar [23]. The only relevant time constraints from Gran Paradiso itself are zircon fission track ages of 30 ± 1 Ma, related to cooling below 225 ± 25°C (e.g. [24]), presumably at less than 10 km depths. The limited geochronological information leaves the exhumation velocity relatively poorly constrained.

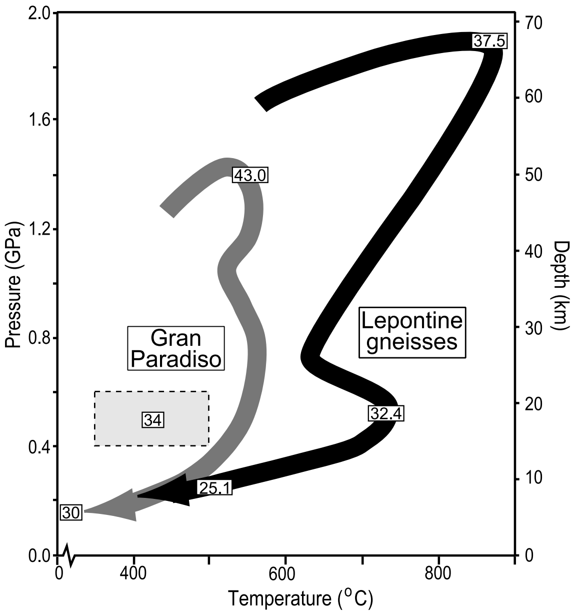

Fig. 2. PTt trajectories of the two areas considered. Values along paths denote age determinations in Ma, depths calculated assuming lithostatic pressure and a bulk density of 2.8×10^3 kg/m^3. For details, see Brouwer [2], Brouwer et al. [4] and the text. References for geochronology: 43.0 Ma, Rb–Sr white mica (Meffan-Main, pers. commun.), 34 Ma, Rb–Sr white mica from the unit overlying Gran Paradiso [23], 30 Ma, zircon fission track cooling below 225 ± 25°C (e.g. [24]), 37.5 Ma, Sm–Nd garnet–clinopyroxene [19], 32.4 and 25.1 Ma, U–Pb SHRIMP zircon [20].

2.3. *Geometry of the Alps: arc development and upper mantle structure*

The differences in the metamorphic histories of the study areas may in part reflect the different positions of the pertinent rocks in the developing orogen. Convergence and collision were essentially orthogonal to the strike of the central Alps [16], whereas the western Alps underwent significant rotation, oblique convergence and out-of-section movements (e.g. [22,25]). During the early stages of collision of Adria with the European plate (50–35 Ma), a NNE–SSW segment of the plate margin served as a zone of sinistral transpression, to accommodate the northward movement of Adria. From 35 Ma onwards, the movement of Adria with respect to the European plate is inferred to have shifted to a northwesterly direction, leading to another 100 km of shortening along the ECORS–CROP seismic section running across the Gran Paradiso massif [22]. These block rotations and out-of-section motions have to be taken into account in the evaluation of the 2-D numerical models discussed below.

Recent high-resolution seismic tomography indicates that below the central Alps, 200–300 km of continental slab is currently present, and a detached oceanic slab may be present at depth [26]. In the western Alps, a much shorter continental slab is still subducting, and high-velocity structures at greater depth have been interpreted to represent detached segments of continental and oceanic slab. Combination of these data suggests that at some point after the onset of continental lithosphere subduction the oceanic slab detached and sank away. The current rupture of the continental slab appears to progress from the western towards the central Alps [26].

3. Hypotheses for late-orogenic high-temperature metamorphism

Several hypotheses have been proposed to explain late-orogenic medium-pressure to low-pressure, high-temperature metamorphism. We will focus on two mechanisms that, at first inspection and at least qualitatively, may explain the main features of the PTt evolutions observed in the studied rocks by accounting for late-stage heating in an orogenic setting. The two mechanisms are: (1) detachment or breakoff of the subducting slab and the associated rise of hot asthenospheric material [6,7], and (2) heat production in a wedge of tectonically accreted radiogenic material [10].

Shallow detachment, or breakoff, and removal of the subducting slab allow an influx of hot asthenospheric material (Fig. 3b), and have been invoked to explain late orogenic magmatism in the Alps [5]. Conduction of heat upward through the overriding plate potentially affects rocks, previously metamorphosed at high pressures, during their exhumation.

Classically, radiogenic heating of thickened continental crust has been considered a likely explanation for heating in an orogenic setting (e.g. [27]). There is, however, a growing body of evi-

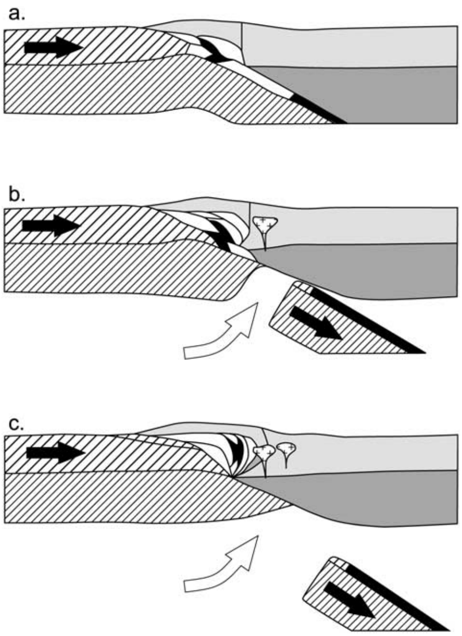

Fig. 3. Processes associated with slab detachment or break-off, modified after Davies and Von Blanckenburg [7]. (a) Oceanic lithosphere subduction is followed by subduction of continental lithosphere. (b) The subducted lithosphere detaches and sinks into the mantle. The gap fills with asthenospheric material, causing melt generation in the overriding lithosphere. (c) Rebound due to the increased buoyancy after removal of the slab causes some uplift in the orogen.

dence indicating an Eocene age of the Alpine HP metamorphism (e.g. [19,28]). As a consequence, the time span between HP metamorphism and late-stage heating is about 15 million years, which is much shorter than previously thought. Jamieson et al. [10] carried out a numerical study explicitly aimed at relatively hot thermal evolutions during orogenesis. Additional heat is produced due to the accretion of excessive amounts of upper crustal radiogenic material in the crustal and/or mantle wedge directly overlying the subducting lithosphere. This wedge is referred to as Tectonically Accreted Radiogenic Material (TARM). A key result of this study is that some of the rocks moving through the wedge undergo heating during the early stages of decompression. Similar scenarios were also modelled by a different group [29,30]. In addition, Engi et al. [31] proposed a modification of this model, in which TARM is not present in the form of a large crustal wedge, but is emplaced as sheets in the subduction channel.

4. Thermomechanical modelling

The model studies outlined below describe the thermal evolution of a 2-D cross section through a subduction and collision zone (Fig. 4). We use a kinematic thermomechanical model based on a model that investigated the feasibility of detachment of part of a subducted lithosphere [32]. The current model was developed to investigate the thermal implications of shallow slab detachment on the overriding plate [9]. Temperature changes are calculated by solving the heat transfer equation numerically using finite difference methods. The geometry of the model and the accompanying thermal boundary conditions are depicted in Fig. 4a. Advection takes place solely in the subducting part of the slab where its velocity is determined by the convergence velocity between the two plates, hence all heat transfer in the overriding plate takes place by conduction. Heat is generated through friction at the plate contact and by downward exponentially decreasing radiogenic heat production in the crust.

The overriding plate is assumed to be stationary and undeformable, so the mechanics of exhumation of deeply subducted material are not incorporated explicitly. However, physical and numerical modelling results suggest that buoyant rise or forced return flow of subducted material back up the subduction channel is possible [33–35]. We focus on the thermal evolution along the plate contact, assuming for simplicity that the pertinent HP rocks move upward along this contact through the evolving temperature field. In this case, a thermal history involving cooling during initial decompression followed by a stage of re-heating at shallower depth prior to final exhumation requires either a transient heat pulse, or an inverted temperature gradient along the plate contact to allow for cooling, re-heating and final cooling.

Dedicated model runs for slab detachment and TARM, start with the subduction of a 50 million year old oceanic lithosphere with a velocity of

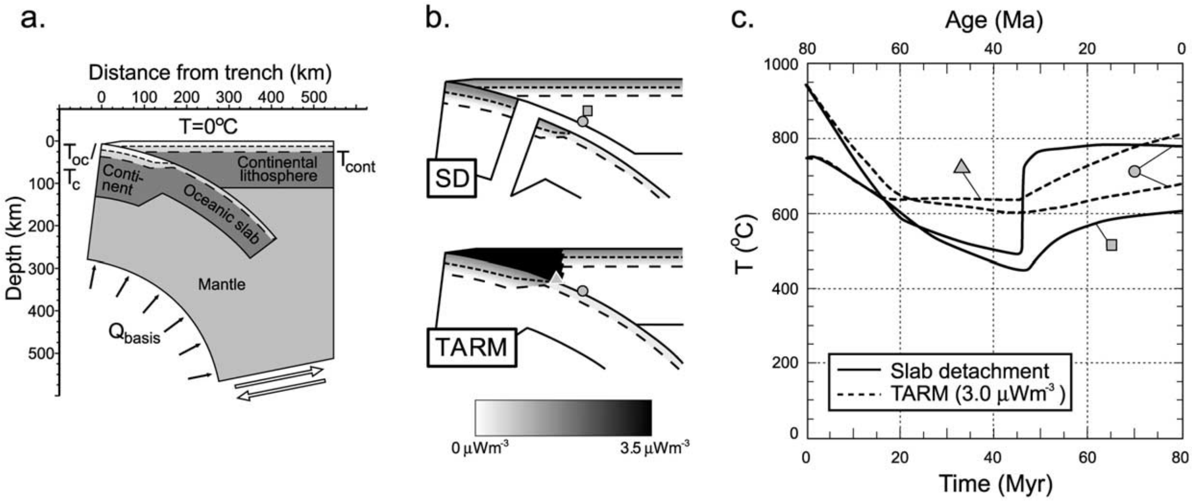

Fig. 4. (a) Geometry and time-dependent thermal boundary conditions of the subduction zone model. Continental and/or oceanic geotherms are applied at the vertical boundaries with a constant zero-temperature at the surface. At the lower left boundary a constant heat flux boundary condition is applied. The vectors at the bottom boundary indicate conductive heat transfer in that direction only. Parameters used: convergence velocity = 1 cm/yr, width of ocean–continent transition zone = 50 km, surface heat flow of the subducting continental lithosphere = 80 mW/m^2, radiogenic heat production of TARM material = 3.0 μW/m^3. Oceanic lithosphere thickness and initial thermal structure correspond to 50 Myr old oceanic lithosphere. (b) Geometry of the slab detachment and TARM models. Markers indicate locations at 2.5 and 10 km from the plate contact. (c) Temperature–time evolution of the slab detachment and TARM models for the locations indicated in panel (b). Onset of continental lithosphere subduction after 30 Myr of oceanic lithosphere subduction. Slab detachment is calculated to occur 15.5 Myr after the onset of continental lithosphere subduction; in the TARM model convergence is stopped at that time.

1 cm/yr. After 30 Myr, continental lithosphere arrives at the trench and starts to subduct. These parameters are chosen for their consistency with palaeogeographic reconstructions of the Piemonte–Ligurian realm [15–17,36–38]. See Fig. 4a for other important model parameters and their values.

4.1. Slab detachment

The model is internally consistent in that the integrated strength of the slab and the forces acting on it are monitored to calculate the time and depth of slab breakoff (for details see Van de Zedde and Wortel [9]). At the onset of continental lithosphere subduction, the strength of the slab decreases rapidly due to the introduction of weak crustal material, while the increased buoyancy causes upward directed forces. Breakoff occurs within the continental slab, near the transition from oceanic to continental lithosphere, where the integrated strength of the slab is at a low [32]. Once the slab detaches and sinks into the mantle, hot asthenospheric material replaces the sinking slab and heats the remaining slab and the overriding plate from below (Figs. 4b and 5a).

With the parameter values selected for the Alps (Fig. 4a,b) slab breakoff is calculated to occur 15.5 million years after the onset of continental lithosphere subduction. The depth at which the slab detaches is relatively shallow (30 km), allowing the hot asthenosphere to well up to crustal levels. The thermal evolution of the overriding plate after slab detachment is characterised by a fast temperature increase near the former plate contact. At a depth of about 60 km and at 2.5 km from the plate contact, this results in a temperature increase of more than 250°C in only a few million years (Fig. 4c). At larger distances, the temperature rises much more gradually and the increase is smaller.

As suggested by Von Blanckenburg and Davies [5] for the case of the central Alps, it seems possible that slab detachment induces partial melting

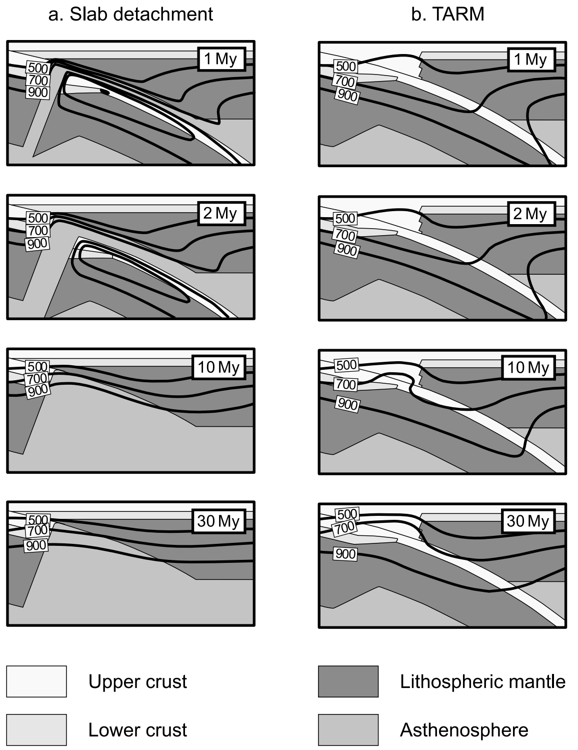

Fig. 5. The thermal evolution of the plate boundary region after slab detachment (a) and that in response to the presence of a TARM wedge (b). (a) Slab detachment is calculated to occur after 15.5 Myr of continental lithosphere subduction. Isotherms at 1, 2, 10 and 30 million years after slab detachment. (b) After 30 million years of oceanic lithosphere subduction and 15.5 Myr of continental lithosphere subduction convergence is halted. Isotherms at 1, 2, 10 and 30 million years after the cessation of subduction.

of fertile rocks in the overriding plate. The current model indicates the possibility of local partial melting in the mantle lithosphere, and that asthenospheric melting only occurs in the case of slab breakoff at less than 50 km depth [9,39]. We note, however, that fluids ascending from the subducting oceanic slab may shift the solidus to lower temperatures, and thus enhance partial melting.

4.2. TARM

Jamieson et al. [10] used a coupled thermal–mechanical model of a collisional orogen to investigate the role of excessive radiogenic heating by wedges of tectonically accreted radiogenic material (TARM, $A = 3\ \mu W/m^3$, compared to more typical crustal values of 1–2 $\mu W/m^3$) as a cause of Barrovian, high temperature–medium pressure metamorphism. The terms crustal and mantle TARM refer to the depths at which the accreted crustal material resides (Fig. 4b).

The model elaborates on mechanical models of collisional orogens, in which the lithospheric mantle subducts while the crust of the downgoing plate is taken up in the orogen, and eventually exhumed due to the coupled effects of tectonic transport and erosion (e.g. [40]). The incorporation of a mantle TARM, a crustal TARM or a combined crustal and mantle TARM causes additional heat production in comparison with the values expected for a standard distribution of radiogenic material.

The model results of Jamieson et al. [10] reveal that there are only two cases in which the presence of a mantle TARM would have a significant effect on the thermal history of rocks that eventually become exhumed: (1) if convergence ceases, such that advective cooling in the subduction zone is effectively stopped, or (2) if erosion rates increase, such that material just above the mantle TARM is exhumed too rapidly to allow conductive cooling during exhumation. The presence of a crustal TARM is more effective in heating material that is eventually exhumed, because the crustal wedge itself is subject to exhumation. An additional effect is that a crustal TARM is a transient heat source, because it is only active until it is exhumed and eroded. Due to the model geometry only material from crustal depths can become exhumed, whereas HP metamorphic rocks from the deeply subducted crust or mantle will not return to the Earth's surface. Rocks undergoing Barrovian metamorphism in these models have not experienced pressures in excess of 1.2 GPa, nor do they show any cooling during initial decompression followed by a temperature increase [10].

In order to compare the effects of a TARM wedge with those of slab detachment, a model was developed which incorporates a wedge of highly radiogenic material ($A = 3\ \mu W/m^3$) overlying the subducting lithosphere (Fig. 4b). The slab is not allowed to break and sink away, even when the forces acting on the slab exceed its strength.

In the adapted model, the TARM wedge is emplaced at the start of the model run, and it is not removed by upper plate deformation and erosion. As a consequence, the temperature increase caused by the presence of the TARM wedge is overestimated.

The adapted TARM model yields no evidence for a fast temperature increase at any monitoring point in the model. Only in case subduction is assumed to stop, the in situ temperature increase within the TARM wedge amounts to about 100°C, 15 million years after cessation of convergence (Fig. 4c).

4.3. Comparison of the model results for the two hypotheses

A comparison between the slab detachment and TARM models reveals interesting differences and similarities between the thermal evolutions of the overriding lithosphere (Fig. 5). In both models the isotherms rise, either due to slab detachment or due to relaxation of the suppressed isotherms after cessation of convergence, so material points within the overriding plate may experience a temperature increase.

The thermal effect of a TARM wedge is entirely independent of the nature and rheology of the downgoing plate. For the TARM model to achieve a significant in situ temperature increase, convergence must cease, and the temperature increase is much slower in the TARM model than in case of slab detachment. Instead of an almost instantaneous thermal response, heating will take more than 10 million years after subduction stops (Fig. 5b). If we suppose a slice of crustal material moves up along the plate contact, the bulge of the 500°C isotherm in the TARM model indicates that initial cooling of the slice could be followed by a stage of re-heating (Fig. 5b, top panel). We note, however, that this bulge is restricted to the TARM wedge itself, and that it exists only because the TARM wedge was present from the start of the model run, which therefore had tens of millions of years to heat up the lower part of the wedge. In the original TARM model [10] the rocks constituting a crustal TARM are exhumed and their preferential exhumation due to weakening induces cooling after peak temperature metamorphism.

In summary, a temperature increase due to slab detachment is fast and transient. High temperatures due to TARM are persistent in our model because the overriding plate does not deform, precluding removal of the crustal TARM wedge. The thermal effect of the TARM wedge and that of slab detachment affect similar length scales in the cross-section modelled. Along-strike in the orogen, however, their thermal effect may in reality be different. Depending on the geometry of plate convergence, a TARM wedge could extend over long distances along the strike of an orogen. Regarding slab detachment, Yoshioka and Wortel [41] have shown that an initial tear in the slab can propagate laterally possibly giving rise to along-strike variations in the timing of a thermal overprint. Lateral propagation of slab breakoff may be hindered by major inherited discontinuities such as transform faults [42], limiting its thermal effect along the strike of the orogen.

5. Comparison of model results with observations

The results of our numerical models outlined above show that both slab detachment and the development of a TARM wedge can provide the heat required to explain a stage of re-heating during exhumation, and that their thermal effects affect similar length scales in 2-D. Therefore, neither the magnitude of the temperature increase, nor the length scale of the medium-pressure high-temperature metamorphism can as such be used to discriminate between the two processes. However, the time scales involved, as well as the kinematics of exhumation are crucial. Below, we compare the model results with the results of our field-based studies in the central and western Alps, taking into account the geodynamic evolution of the areas and the PTt trajectories deduced for the rocks in question (Fig. 2).

We previously presented the results of our numerical model using stationary marker points that record the thermal evolution at a specific location (Fig. 4). To compare our model results with the PTt trajectories derived for the two field areas, we construct synthetic PT paths. To derive these PT paths, the temperature at locations just above the plate contact is recorded at progressively shallower depths. The model PT paths are indicative of the predicted thermal evolution of a small volume of rock moving upward along the subduction channel (analogous to the exhumation process detailed in Engi et al. [31]). Therefore, although exhumation is not explicitly incorporated in our model, an assessment of the thermal evolution of a small exhuming rock volume is nevertheless possible. The upward velocity is estimated by combining the pressure estimates with geochronological information as displayed in Fig. 2. Note that the accuracy of the exhumation scenarios is largely determined by the availability of geochronological data that are linked to PT estimates. For this reason, the constructed scenarios are first-order estimates, and because of the limited data available, the exhumation rate of Gran Paradiso is relatively poorly constrained. Although the synthetic PT paths are deduced from the same model runs, the paths differ for the two field areas because their exhumation histories are not the same. We therefore discuss the PT evolutions of the two areas separately.

5.1. Lepontine gneisses, central Alps

For the Lepontine gneisses the age of high-pressure metamorphism is taken as the start of exhumation along the plate contact. Exhumation starts at 37.5 Ma and its velocity (in vertical sense) is roughly 10 mm/yr (50 km in 5 million years). After 32.5 Ma exhumation proceeds at a much slower rate (lower panel of Fig. 6a). With the parameter values selected for the Alps, the slab detachment model predicts breakoff at 34.5 Ma (Fig. 4c). The synthetic pressure–time path (Fig. 6a, lower panel) indicates that the exhuming volume of rock is at a depth of 40 km at the predicted time of breakoff. Since detachment is calculated to occur at a depth of around 30 km, the heat of the upwelling hot asthenosphere affects the exhuming rocks. After initial cooling due to exhumation, the marker point records a temperature increase of more than 250°C (Fig. 6a).

Using the same exhumation scenario we construct a model PT path for TARM (Fig. 6a). The accreted radioactive material affects the overall temperatures in the subduction zone considerably. The exhuming rock volume records overall higher temperatures, but shows a gradual temperature increase of only about 50°C when travelling towards the TARM wedge and through its base. The model PT path does not reproduce the rapid increase recorded by the Lepontine gneisses.

Both the time scale involved in heating and the cessation of convergence, needed in the TARM model to achieve an in situ thermal signal, are in conflict with the geological data from the Penninic zone of the Alps. Continental lithosphere subduction started at or after 50 Ma, while the re-heating culminated at 32.5 Ma in the central Alps. This leaves a maximum of 18 million years between the onset of continental collision and the observed re-heating, while the 37.5 Ma age of HP metamorphism indicates that subduction of continental lithosphere continued during at least part of this period. On the other hand, all data indicate that there was a considerable period, estimated to have lasted at least 40 but possibly 70 My (see Section 2), of oceanic and continental lithosphere subduction prior to collision. It is therefore quite possible that some highly radiogenic material accumulated at the subduction zone trench, although its contribution to heating of material in the wedge can only have been localised and minor because of continuous advective cooling (see also [9]).

The slab detachment model predicts the characteristics of the late-stage temperature increase at shallow depth during exhumation and therefore seems to be a more viable hypothesis to explain the Lepontine metamorphism in the central Alps. Recent tomographic imaging of the upper mantle beneath the Alps also suggests that the oceanic slab detached sometime after the onset of continental lithosphere subduction [26].

5.2. Gran Paradiso, western Alps

Gran Paradiso is thought to be derived from Briançonnais ribbon continent, which was part of the overriding plate during subduction of the Valais oceanic lithosphere (e.g. [21]). Comparison

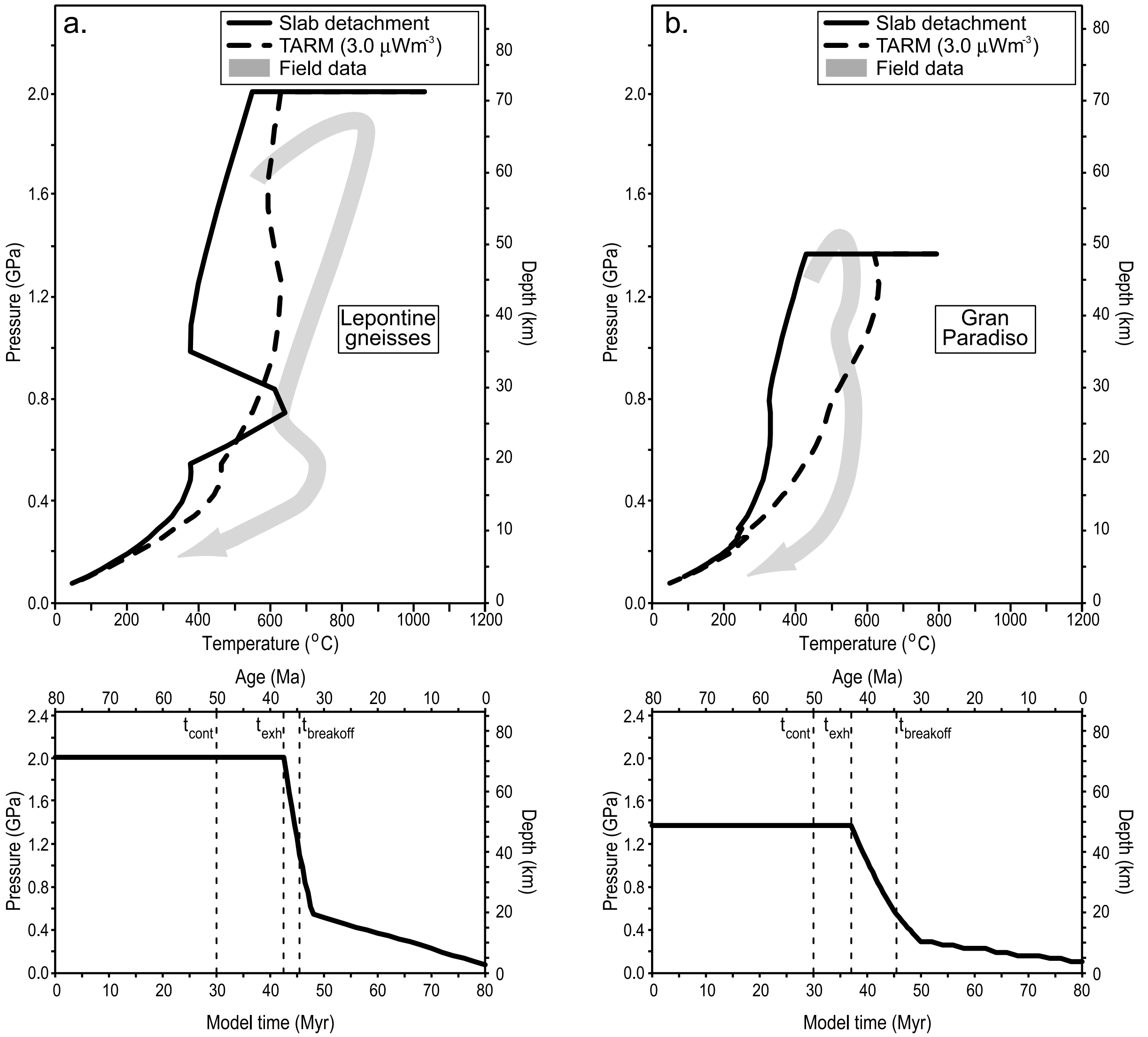

Fig. 6. Synthetic PT paths derived from the model runs depicted in Figs. 4 and 5, using the exhumation velocity (based on the information in Fig. 2) as experienced by the Lepontine gneisses (a) and Gran Paradiso (b). Note that the paths reflect the temperature predicted for stationary points 2.5 km upward from the plate contact. The depth at which the temperature is recorded is related to the exhumation velocity of the pertinent rocks (see lower two panels). Key: t_{cont} = onset of continental lithosphere subduction (model input parameter); t_{exh} = time at which the rock volume starts moving upward along the plate contact (based on the age of HP metamorphism, Fig. 2); $t_{breakoff}$ = time of slab detachment (model result).

of the synthetic PT path with that derived for the field area is therefore more straightforward. The model PT path is deduced assuming exhumation started at 43 Ma, the time of high-pressure metamorphism. The timing of re-heating is poorly constrained, but cooling of Gran Paradiso below 225°C was dated at 30 Ma using zircon fission tracks (Fig. 2). We assume that by this time the rocks had arrived at less than 10 km depth (Fig. 6b, lower panel).

The model PT path was constructed for the slab detachment model run presented before, which predicts breakoff at a depth of 30 km at 34.5 Ma (Fig. 4c). At this time, the exhuming rock volume is at 20 km depth, well above the depth of breakoff. This explains why the exhuming rocks experience very limited re-heating (only about 10°C, Fig. 6b), which is even less than the re-heating derived from the field data.

The PT path derived for the TARM model is based on the same exhumation scenario as for slab detachment (Fig. 6b). The dashed PT curve is at significantly higher temperatures than the path for the SD model, but re-heating during exhumation is not predicted, although the cessation of convergence produces a slight decrease in cooling rate. At the onset of exhumation, at around 50 km depth, the exhuming rock volume enters the TARM wedge from below. The resulting brief stage of heating occurs deeper than the re-heating observed in the rocks (around 37 km; compare the dashed and light grey curves in Fig. 6b).

Neither of the two models yields PT paths that match the field data very closely. Note, however, that only the SD model predicts a stage of cooling during decompression, followed by a small amount of re-heating and then final cooling and exhumation. The timing of the re-heating recorded in Gran Paradiso is weakly constrained to predate 34 Ma (Fig. 2). The time of breakoff predicted by the model may therefore not match the geologic data for the western Alps as closely as those for in the central Alps. If breakoff occurs somewhat earlier in the model run, Gran Paradiso would experience its thermal effects at somewhat greater depth, and from a closer distance, which would provide better correspondence between synthetic and field PT paths. Earlier breakoff in the western Alps would not be unreasonable, because the tear in the slab is likely to propagate laterally [41]. This tentative hypothesis is supported by recent seismic tomography showing a clear gap in the slab below the western Alps [26].

5.3. General considerations

A striking difference between the synthetic PT paths for TARM and SD and the paths derived for the field areas is that the overall temperatures recorded in the overriding plate of the model are considerably lower than those in the rocks. In deducing model PT paths we assume that the exhuming rocks instantly attain the ambient temperature at their position in the model space. In reality, it is possible that the velocity and volume of the exhuming body prevented it from recording the ambient temperature, or that a time-lag occurred. Alternatively, one could envisage a combined scenario, where the presence of highly radiogenic material causes overall higher temperatures, and the occurrence of slab detachment provides the additional heat for re-heating. For the Lepontine gneisses the difference may, in part, be due to the fact that the rocks likely originate from the (warmer) subducting plate instead of the overriding lithosphere.

When assessing the possible roles of slab detachment and TARM, arguments from palaeogeographic reconstructions and other geological evidence should be taken into account. To accumulate the material for a substantial TARM wedge requires tens of millions of years of subduction and very efficient accumulation of sediments at the trench. The material then needs additional time to achieve its maximum thermal impact. In the case of the western and central Alps estimates range from 21 to a maximum of 60 million years of oceanic lithosphere subduction, which, in combination with a relatively slow plate convergence, appears rather limited for TARM to have a substantial impact.

As reported by Von Blanckenburg et al. [18], the magmatic rocks spatially associated with the Lepontine metamorphism have a distinct upper mantle signature. To explain this, some process involving transfer of material upward from mantle levels has to be invoked. The upper mantle signature can not be accounted for in a TARM scenario.

If slab detachment indeed caused the observed post-collisional heating of the Gran Paradiso rocks, we would expect to find a similar thermal evolution in the Monte Rosa and Dora Maira massifs (Fig. 1). Indeed, postcollisional re-heating has been reported from all three Internal Penninic Nappes [1]: the Monte Rosa massif (to 465°C), the Gran Paradiso massif (to 494°C), and the northern part of the Dora Maira massif (to 482°C). The occurrence of staurolite in the Monte Rosa massif [43] suggests that peak temperatures may even have been higher. These observations support our inferences of the regional implications of the occurrence of slab detachment. However, it should be noted that the differences between the estimated peak temperatures are small and the amounts of heating poorly constrained, precluding discussion in terms of gradients along the arc of the Alps.

In view of the existing evidence for transpressional deformation [22] and block rotations (e.g. [25]) in the western Alps it seems likely that, at the time of slab breakoff and re-heating, rocks presently exposed in the western Alps were located much closer to the rocks now found in the central Alps. The rocks of the Gran Paradiso massif may thus have experienced re-heating while residing in a geographical position closer to the rocks of the Lepontine gneiss dome, in response to slab breakoff in that segment of the Alps. The relatively low magnitude of re-heating (40°C) may reflect the position of the pertinent rocks in the system, not only with respect to distance above the plate contact, but also regarding the precise geographical location of the detaching section of the slab. Re-heating in the Gran Paradiso massif may be due to slab detachment, albeit that the detachment process did not necessarily occur underneath the present-day western Alps.

6. Discussion

6.1. TARM sheets instead of a TARM wedge?

Engi et al. [31] proposed that, with a modified geometry, TARM may indeed play a role in the thermal evolution of the central Alps. TARM would be present in the form of sheets of highly radiogenic material in the subduction zone, rather than a wedge in the crust or mantle. Along the Insubric Line (Fig. 1), a zone of strongly deformed crustal material could represent such a TARM sheet and this zone was used to estimate its composition and heat productivity. TARM sheets (5 or 10 km thick, $A = 2.67\ \mu W/m^3$) were then incorporated in kinematic numerical models of a subduction zone to assess their impact on its thermal evolution [31,44]. It was suggested that TARM sheets produce sufficient heat to account for overall relatively hot PT paths, as well as for Lepontine re-heating.

Upon inspection of the models, we find that TARM sheets are indeed effective in causing an overall high temperature evolution of rocks being subducted and exhumed along the subduction channel. However, a late stage of re-heating following initial cooling and decompression occurs in models with and without TARM sheets [31]. The re-heating seems to be caused by the peculiar geometry of the subduction system after the onset of erosion, in which part of the slab delaminates and is stuck in the subduction zone, causing heating of material that passes overhead on its way to erosional exhumation. Re-heating then occurs regardless the presence or absence of TARM sheets. Therefore, the TARM sheet model is not pertinent to the Lepontine overprint in the Alps, although it offers a much more realistic geometry than the original TARM wedge model [10], while maintaining an overall hotter subduction system.

6.2. Exhumation of high-pressure rocks in the Alps

The exhumation of high- to very high-pressure rocks carrying evidence for metamorphism at mantle depths remains problematic. Erosion alone cannot account for the exhumation of rocks from tens of kilometres depth [45], and buoyancy has been put forward as the driving force of exhumation of crustal rocks through the subduction channel (e.g. [33,34]). In these models, large coherent slices of crustal material decouple from the mantle lithosphere at great depth, followed by exhumation of the upper part of such slices, driven by the buoyancy of a root of crustal material. Exhumation largely depends on the coherence of the crustal slices involved. Geochronological data indicate that the exhumed HP rocks in the Alps were metamorphosed shortly after the onset of continental lithosphere subduction. Therefore, it seems unlikely that rocks, subducted to depths of 65 km like the Lepontine gneisses, or to more than 100 km like other Penninic rocks (e.g. [46]), were pushed back up the subduction zone by the buoyancy of large slices of continental material at greater depth.

Alternatively, it has been proposed that the subduction channel acts as a zone in which small fragments of crustal rocks are subducted and exhumed, after a reversal of the fault kinematics [31]. The movement of the slices in such a Tectonic Accretion Channel (TAC) would largely be driven by plate convergence during subduction, and by buoyancy during exhumation. It remains a question, however, whether slices of crustal material have enough coherence and buoyancy, relative to the surrounding thickened lower crust and subcontinental mantle, to drive their exhumation. It has been suggested that slab breakoff may trigger the reversal of movement within the TAC by changing the overall stress regime [31].

Recent numerical models invoked ductile forced return flow of weak material out of the subduction channel, due to narrowing of the channel at depth [35]. We speculate that such narrowing could be the response to slab breakoff. However, the continuous and rapid cooling of high-pressure rocks during exhumation, which is predicted by these models, contrasts with our observations from the Alps.

7. Conclusions

PTt trajectories from the central and western Alps indicate that the high-pressure metamorphic rocks cooled and were re-heated during exhumation. Available geochronological data indicate that the thermal signal recorded in our rocks and represented in the central Alps by the Lepontine gneiss dome requires a fast and transient heat source, or a high temperature zone through which the rocks have moved. 2-D numerical models of slab detachment and a TARM wedge show that both mechanisms can potentially provide sufficient heat to cause late-stage heating in the developing orogen. However, heating due to a TARM wedge requires cessation of subduction and a time-lapse of tens of millions of years, whereas sinking of the slab after its detachment causes a fast and transient temperature increase in the overriding lithosphere. In view of the time constraints we prefer the process of slab detachment to the presence of a TARM wedge as the principal cause for the Lepontine late-stage heating in the central Alps.

It is unlikely that a TARM wedge caused the temperature increase observed in the western Alps, because of the short time span available for cooling and subsequent heating, as well as continuing oblique subduction when the rocks were re-heated. The observed re-heating in the western Alps may have occurred in response to slab detachment in that segment of the belt. Alternatively, the Gran Paradiso massif may have experienced re-heating due to a slab breakoff event in the central Alps, followed by transport away from that domain due to out-of-section movements and block rotations in response to oblique convergence between Adria and Europe.

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