Rapid formation and exhumation of the youngest Alpine eclogites: A thermal conundrum to Barrovian metamorphism

Andrew J. Smye a,⁎, Mike J. Bickle a, Tim J.B. Holland a, Randall R. Parrish b, Dan J. Condon b

⁎ Corresponding author. Tel.: +44 1223 333400; fax: +44 1223 333450.
E-mail address: as859@cam.ac.uk (A.J. Smye).

a Department of Earth Sciences, University of Cambridge, Cambridge, CB2 3EQ, UK
b NERC National Isotope Geoscience Laboratories, Kingsley Dunhem Centre, Keyworth, Nottingham, NG12 5GG, UK

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1. Introduction

High-pressure (HP) metamorphic rocks are a ubiquitous feature of Phanerozoic mountain belts. Their occurrence provides important constraints on both the transfer of material between the crust and mantle, and also the timing of continental collision within zones of active and past convergence (De Sigoyer et al., 2000; Leech et al., 2005; Parrish et al., 2006; Rubatto and Hermann, 2001). Whilst subduction provides a plausible mechanism by which tracts of oceanic and continental lithosphere are conveyed to upper mantle depths, the processes responsible for exhuming such rocks back to Earth’s surface are less well understood (e.g. Agard et al., 2009, and references therein).

Within the typical orogenic cycle (ultra)high-pressure (UHP) metamorphism occurs early, linked to subduction of intervening oceanic realms, before the inception of continental collision which thickens the crust and drives subsequent Barrovian metamorphism. This accounts for commonly observed amphibolite–gneisschist facies overprinting of blueschist–eclogite facies metamorphic rocks (e.g. De Sigoyer et al., 1997, 2004; England and Richardson, 1977). High-precision radioisotope geochronology of both (U)HP and Barrovian metamorphic events allows calculation of average exhumation rates of (U)HP bodies. Recently, this approach has shown that exhumation rates are of the same order of magnitude to plate velocities—cm·a−1 (e.g. Baldwin et al., 2004; Meffan-Main et al., 2004; Parrish et al., 2006; Rubatto and Hermann, 2001). Such rates of exhumation question the dominance of conductive heat transfer over timescales of tectono-metamorphic evolution in orogenesis. In mountain belts such as the Alps and the Himalayas, where exposed rocks record both Barrovian and (U)HP metamorphism associated with plate convergence it should be possible to assess both the duration of thrusting and subsequent conductive relaxation heating. This is of fundamental importance to understanding the rates and mechanisms responsible for driving tectono-metamorphic evolution in areas of orogenesis.

The Tauern Window (Fig. 1) exposes the largest coherent eclogite facies unit within the Eastern Alps. Eclogites sensu stricto and eclogite facies metasediments pertaining to the European margin are exposed in a nappe which, following HP metamorphism, experienced regional Barrovian metamorphism associated with emplacement of the Austroalpine nappes.Tauern Barrovian metamorphism provided the impetus behind pioneering studies of the thermal budget of tectonically thickened crust (Bickle et al., 1975; England, 1978; England and Richardson, 1977; England and Thompson, 1984;
Oxburgh and England, 1980; Oxburgh and Turcotte, 1974). However, despite extensive petrological study (Frank et al., 1987; Getty and Selverstone, 1994; Holland, 1979a,b; Miller, 1974) the age of eclogite facies metamorphism and therefore the duration of conductive heating are poorly constrained. Previous geochronological understanding relies heavily on the ⁴⁰Ar–³⁹Ar system (Kurz et al., 2008; Zimmermann et al., 1994), which is highly susceptible to excess ⁴⁰Ar contamination under HP conditions (e.g. Sherlock and Kelley, 2002; Warren et al., 2010). Further geochronological studies have been hampered by isotopic disequilibrium (Van Breezen and Hawkesworth, 1980), a paucity of datable accessory phases (Miller et al., 2007) and the lack of a quantifiable link to P–T conditions (Glodny et al., 2005). As a result, despite the Eastern Alps being one of Earth's best studied orogens, the timescales of its evolution are currently uncertain. This paper presents results of a combined thermobarometric, geochronological and thermal modelling study which show that eclogite formation, exhumation and subsequent Barrovian metamorphism all occurred in under 10 Ma—within an order of magnitude quicker than previously thought. We use high-precision U–Pb allanite geochronology to illustrate the potential that allanite has as a prograde geochronometer in high grade metamorphic terranes.

2. Tauern Window eclogites

The Tauern Window exposes Penninic nappes of the Alpine orogen's lower plate, which are observed in a geometry reflecting exhumation, post-subduction associated with closure of the Valaisan oceanic realm (Fig. 1). Eclogites and associated HP metasediments outcrop within the Eclogite Zone (south-central Tauern Window) — a tectonic sliver 15 km in length, intercalated between a crystalline basement complex — the Venediger Nappe, and an incomplete ophiolite suite — the Glockner Nappe. The Eclogite Zone comprises abundant metre to hundred metre scale eclogite boudins and pods hosted by a metasedimentary matrix, which is dominated by calc-schists, metapelites and quartzites. Both mafic and sedimentary protoliths have experienced eclogite-facies metamorphism. The combination of mafic igneous and sedimentary lithologies supports interpretation that the succession was deposited on the southern passive margin of the European continent prior to Tertiary subduction and collision (Miller, 1974; Ratschbacher et al., 2004).

2.1. Tectono-metamorphic evolution

The Eclogite Zone behaved as a coherent unit within the Alpine orogenic episode and preserves petrographical signatures of three discrete metamorphic events. Relicts of its prograde history are limited to mica, chloritoid and epidote inclusions in garnets. Pseudomorphs after lawsonite, within garnet poikiloblasts, have been inferred by several authors (Dachs, 1986; Droop, 1985; Spear, 1986). The HP event is typified by garnet–omphacite–kyanite–phengite assemblages in mafic eclogites (Holland, 1979b) and garnet–chloritoid–kyanite–phengite parageneses in metaepichotites (Smye et al., 2010). Numerous thermobarometric calculations using peak eclogite-facies mineral assemblages yield a range in P–T conditions from 20 to 26 kbar and 550–600 °C (Franz and Spear, 1983; Holland, 1979b; Hoschek, 2001; Smye et al., 2010; Stöckhert et al., 1997). During exhumation the Eclogite Zone is thought to have been tectonically inserted between the underlying Venediger nappe and beneath the overlying Glockner nappe (Behrmann and Ratschbacher, 1989) under blueschist-facies conditions, indicated by partial replacement of eclogite-facies amphibole and pyroxene by glaucophane (Holland and Richardson, 1979). Regionally penetrative greenschist–amphibolite facies metamorphism (ca. 7 kbar and 520–570 °C, Zimmermann et al., 1994) overprinted previous metamorphic assemblages during conductive heating associated with isotherm relaxation after emplacement of the Austroalpine nappes (Bickle et al., 1975). Numerous radiometric dating studies have shown that this event occurred ca. 27–32 Ma. Glodny et al. (2005) performed Rb–Sr analyses on coegenetic white mica, titanite, amphibole and plagioclase from a structurally discordant vein assemblage in a greenschist retrogression aureole within mafic eclogite. They obtained an isochron age of 31 ± 0.5 Ma (MSWD = 0.63). This age is supported by the data of Gleißner et al. (2007), who carried out Rb–Sr isotopic analyses of a pseudomorphic assemblage after blueschist facies lawsonite in the Glockner nappe. A multimodal internal isochron involving white mica, apatite, epidote, chloritoid, calcite and albite yields an age of 29.82 ± 0.54 (MSWD = 2.2). The age is interpreted to
represent syntectonic growth of the greenschist facies matrix assemblage. Similarly, Inger and Cliff (1997) present white mica, epidote and whole rock Rb–Sr isotopic data from eleven different localities from within the Eclogite Zone and Glockner nappe. All of the ages lie between 27 and 31 Ma and are interpreted to record greenschist facies metamorphism concomitant with penetrative deformation, influx of fluids and resetting of Sr isotopes. Phengite $^{40}$Ar–$^{39}$Ar ages obtained from Eclogite Zone lithologies range between 32 and 42 Ma (Kurz et al., 2008; Ratschbacher et al., 2004; Zimmermann et al., 1994) and are variably interpreted to represent cooling from high pressure metamorphism.

Both the Venediger and Glockner nappes appear to have experienced a common metamorphic history with the Eclogite Zone subsequent to the blueschist event (Holland and Ray, 1985). Our geochronology is consistent with the pseudosection calculations. Sample TH-680 escaped pervasive overprinting during the Barrovian metamorphic event. Zoned epidotes with allanitic cores and clinozoisite rims are present as elongated lozenges (150–900 μm length; 50–200 μm width) which are wrapped by the rock’s crenulated phengite fabric (S0 +S1), which additionally wraps around garnet poikiloblasts. Proximal to fold hinges, allanite grains are aligned parallel to the limbs of F2 generation microfolds. Euhedral allanite grains are also present as rare inclusions within both core and rim portions of garnet poikiloblasts (Fig. 3a) – indicative of pre-garnet growth. The textural setting of allanite in TH-680 is notably similar to that described by Hoschek et al. (2010) from a garnet–chloritoid–kyanite bearing micaschist collected nearby TH-680, within the Eclogite Zone.

### 2.3. Allanite

Allanite ([Ca, REE, Y]$_2$ (Al, Fe)$_3$Si$_3$O$_9$) (OH) can incorporate weight percents of the LREE inventory and Th in crustal rocks (Hermann, 2002)
Fig. 3. Allanite chemistry: (a) High contrast BSE image of euhedral allanite in garnet poikiloblast. Clin zoisite rims to allanite cores are present in grains included within garnet and also as matrix porphyroblasts. The textural setting of allanite in TH-680 is very similar to that described by Hoschek et al., 2010 of a similar lithology from the Eclogite Zone. (b) False colour X-ray map of Th concentration in allanite 1, TH-680. Euhedral core regions display complex structure relative to Th-poor clin zoisite rims. (c) Chondrite normalised LA–ICPMS REE patterns for allanite core regions and coexisting garnet. Allanite is enriched in LREEs relative to garnet (Fig. 3c). Allanite and garnet contain 10 kbar). Structural formulae for allanite and clin zoisite fractions grew early along the prograde metamorphic path. Further pseudosection calculations imply that garnet growth initiated between 18 and 21 kbar and 550–580 °C, consistent with chemical and petrographic evidence showing that both allanite and clin zoisite fractions grew early along the prograde metamorphic path.

3. Geochronology of metamorphism

Current understanding of the timing of eclogite-facies metamorphism within the Tauern Window is based on Rb–Sr geochronology (Glodny et al., 2005, 2008). However, the known susceptibility of Rb–Sr to isotopic resetting during deformation and retrogressive metamorphism (Thoni...
and Jagoutz, 1992) means that confirmation from a more robust system is required. The U(–Th)–Pb system is the preferred choice given its high closure temperature (∼600 °C), and the potential to demonstrably link ages with P–T conditions.

Typically allanite core regions contain 2–235 ppm U and have Th/U ratios between 1.7 and 21.6. Such low Th/U ratios focused geochronological studies on the U–Pb system. We used U–Pb Isotope Dilution–Thermal Ionisation Mass Spectrometry (ID–TIMS) and U(–Th)–Pb Laser Ablation–Multiple Collector–Inductively Coupled Plasma Mass Spectrometry (LA–MC–ICPMS) methods to date laser-milled separates and in-situ allanite grains respectively. The U(–Th)–Pb data and analytical methods are given in the Supplemental Data Set (Supplemental text S.5; Table S.D.5; Table S.D.6). Preliminary laser ablation studies were hampered by the absence of a suitable allanite standard. Analysis of Tertiary Alpine allanites previously used as standards (Gregory et al., 2007) reveals protracted crystallisation histories and significant spread in single grain U(–Th)–Pb contents. Against a primary zircon mineral standard, analyses of both core and rim portions of zoned grains show that non-radiogenic Pb dominates the total Pb composition (Pb/Pb<0.03). In particular, clinozoisite rim portions contain negligible radiogenic Pb (238U/206Pb<0.15) and thus provide an estimate of the common Pb composition of the rock during allanite growth. Analyses (n = 14) of two allanite grains (allanite 1 and 7) in thin section X1 provide a Tera-Wasserburg lower intercept age normalised to zircon standard 91500 (Wiedenbeck et al., 1995) of 34.6 ± 4.1 Ma (2σ; MSWD = 15) and an initial 207Pb/206Pb composition of 0.8211 ± 0.0015 (95% conf.; Fig. 4a).

Given the lack of a matrix-matched primary standard, this age is not robust enough for geological interpretation. In order to circumvent this, three allanite grains previously used for LA–MC–ICPMS were separated for U–Pb ID–TIMS analyses. Individual grains were extracted from polished thin sections via laser milling of matrix material and were subsequently broken into 50 μm diameter shards. ID–TIMS measurements corroborate observations on U–Pb systematics made from LA–MC–ICPMS measurements. Despite the limited spread in 238U/206Pb compositional space (0.5–5), analyses of eight allanite–clinozoisite shards define a Tera-Wasserburg regression with a lower concordia intercept age of 34.2 ± 3.6 Ma (2σ; MSWD = 3.8) and an initial 207Pb/206Pb composition of 0.8330 ± 0.0014 (95% conf.; Fig. 4b), which is slightly more radiogenic than the 34 Ma average upper crustal lead composition predicted by Stacey and Kramers (1975) (0.8379). Due to low allanite Th/U values, 207Pb/206Pb and 238U/206Pb ratios corrected for ingrowth of 206Pb from the incorporation of excess 238Th (Schärer, 1984), yield an age difference within the uncorrected 2σ age uncertainty. Performing both ID–TIMS and LA–MC–ICPMS analyses on the same allanite is a powerful geochronological approach, combining the spatial resolution of laser ablation and the high precision of ID–TIMS. Although the ID–TIMS Tera-Wasserburg age is within error of the LA–MC–ICPMS age, common Pb compositions are subtly different (Δ(207Pb/206Pb)≈0.0119). Identification of a suitable allanite standard is required to constrain matrix dependent isotopic fractionation for U(–Th)–Pb LA–ICPMS allanite geochronology.

4. Tectonic implications

We interpret the 34.2 ± 3.6 Ma ID–TIMS age as the time at which allanite cores to clinozoisites grew between ~8 and 13 kbar at 400–500 °C (see Figs. 2 and 5) prior to garnet growth during ongoing subduction. The new geochronological data, combined with previously reported data, permit calculation of exhumation rates and also timescales for the process of eclogite formation in the Eastern Alps. Taking the angle of subduction as 45° and a descending slab velocity of 5 cm·a−1, the earliest peak pressure conditions (~26 kbar) would be attained in the subducted margin in ~2 Ma after allanite growth i.e. by ca. 33 Ma. However, given the 2σ uncertainty on the ID–TIMS age, peak pressure conditions are constrained to the interval 29–37 Ma. This corroborates the 31.5 ± 0.7 Ma Rb–Sr age of Glodny et al. (2005), obtained from a range of eclogitic mineral assemblages. The Eclogite Zone was subjected to regionally pervasive Barrovian metamorphism between 27 and 32 Ma (Rb–Sr: Inger and Cliff (1997); Glodny et al. (2005)), which places a limit on the time taken to both form and exhume the eclogite-facies nappe to mid-crustal levels. Therefore, the Eclogite Zone must have experienced ~60 km of exhumation at rates between ~1 and 6 cm·a−1. It is extraordinary, then, that the Eclogite Zone is understood to have been subjected to local recrystallisation in the blueschist facies, prior to Barrovian overprinting as evidenced by the growth of glaucophane at the expense of peak eclogitic omphacite. The P–T conditions of blueschist facies metamorphism are constrained between 7 and 11 kbar and 400–450 °C (Eremkin, 1994; Holland and Ray, 1985). Given that the Eclogite Zone represents transitional crust located on the southern margin of the European continent (Kurz et al., 1998, and references therein), the 29–37 Ma age of eclogite formation critically provides a maximum estimate for the timing of continental collision in the Eastern Alps. This means that a maximum of 10 Ma
The thermal diffusivity of continental lithologies determines that conductive heating driven by relaxation of isotherms in regions of over-thickened crust operates on timescales of the order of tens of millions of years (England and Thompson, 1984). However, high-precision isotope geochronology has recently shown that in some regional metamorphic terranes, peak Barrovian conditions are attained within much shorter durations (Ague and Baxter, 2007; Baxter et al., 2002; Oliver et al., 2000). Disparity between predicted and observed timescales of heating necessitates additional mechanisms to conductive heating. These include: elevated mantle heat flow (Oxburgh and Turcotte, 1974; Stüwe and Sandiford, 1995), increased radiogenic heat production (Huerta et al., 1999; Jameson et al., 1998), shear heating (Grujic et al., 1996; Searle et al., 2008; Whittington et al., 2009), magmatism (Lyubetskaya and Ague, 2010), advective transport of heat by fluids (Bickle and McKenzie, 1987) and advection of heat by tectonics (Burg and Gerya, 2005).

The Tauern Window is a classic locality for modelling the thermal evolution of overthrust terrains (Bickle et al., 1975; Cornelius et al., 1939; England, 1978; England and Richardson, 1977; England and Thompson, 1984; Oxburgh and England, 1980; Oxburgh and Turcotte, 1974; Richardson and England, 1979).Tauern Barrovian metamorphism is understood to have been driven by conductive heating following northward emplacement of allochthonous Austroalpine units during Alpine orogenesis (Oxburgh, 1968). Previous conductive heating models call for a period of ca. 30 Ma post-emplacement of the Austroalpine nappes for the European basement to attain peak conditions of 520–550 °C at 7–8 kbar (see Fig. 5) – thus invoking ages of East Alpine eclogite formation >60 Ma. This is incompatible with our geochronological data, which show that a maximum of 10 Ma passed between eclogite formation and the peak of Barrovian metamorphism. Here we use a one-dimensional thermal model (e.g. (Bickle et al., 1975; Oxburgh and Turcotte, 1974)) to constrain thermo-tectonic scenarios which satisfy rapid (<10 Ma) attainment of Tauern Barrovian conditions.

5.2. The model

The thermal development of the Tauern Window is modelled by a one-dimensional finite-difference approximation to the heat equation following the approaches of Oxburgh and Turcotte, (1974), Bickle et al., (1975) and England, (1978) in which the thermal profile following overthrusting is calculated for different values of total heat generation (radiogenic heat production + mantle heat flow). Additionally, we consider the effect of thrust sheet thickness on the evolving thermal profile. Numerical details of the model are presented in the (Supplemental text 5.6).

The initial thermal profile is divided into two units representing the allochthonous Austroalpine complex and lower plate Penninic basement and cover nappes, including the Eclogite Zone. Diffusivity (κ) is kept constant throughout the profile at 31.54 km²·Ma⁻¹ (~1 mm²·s⁻¹) as temperature dependent feedbacks (Fig. 3 Bickle et al., 1975; Whittington et al., 2005) are only significant over the investigated length- and timescales in the presence of concentrated heat sources such as magmatism and shear heating, which are not applicable to the Tauern. The initial temperature profile of the overthrust sheet is insignificant to the thermal evolution of the system (Bickle et al., 1975) and therefore, we use identical equilibrium geotherm relations (see Appendix A5) for both hanging- and footwall units. The surface temperature is 20 °C for all time steps and we assume a basement-top initial temperature of 20 °C, justified by its 1000 m thick cover sequence (Kurz et al., 1998). The lower boundary condition is defined by a constant temperature gradient at 150 km depth. Constraints on the thickness of the Austroalpine complex are limited due to internal imbrication and the absence of palaeo-horizontal markers. However, an estimate of the sheet’s minimum thickness at the time of over-thrusted is obtained from peak pressures experienced within the Zentralgneiss of the Venediger nappe, during Barrovian metamorphism: 6–14 kbar equating to 20–45 km (this study). These thicknesses are slightly greater than assumed by previous studies (15–30 km – Bickle et al. (1975); England (1978); England and Thompson (1984)) reflecting advances in thermodynamic data used in calculating metamorphic pressures. Radiogenic elements in the Pennine basement are strongly concentrated within the Zentralgneiss—a Variscan calc-alkaline granite body. Measurements by Hawkesworth (1974b) are consistent with an exponential distribution of radiogenic matter (Lachenbruch, 1968, 1970) with a characteristic drop-off length (D) of 8 km and a surface radiogenic heat production (AZ0) of 5.02 μW·m⁻³. Assuming such a distribution, Bickle et al. (1975) calculate an estimate of the total radiogenic heat production (AZ0·D) possible from the basement of 50.16 mW·m⁻² (1.19 HU). Given the lack of constraints, mantle heat flow (qm) is allowed to vary between 20 and 100 mW·m⁻² (0.47–2.39 HU), encompassing values characteristic of stable continental crust to rifting margins (Sclater et al., 1980, 1981). It is important to note that the contribution of heat from the mantle is the single most important parameter affecting the thermal evolution of the system (England, 1978). Previous models invoke an erosional hiatus between emplacement of the Austroalpine at ca. 65 Ma and initiation of erosion within the Oligocene (Fig. 6; Bickle et al. (1975); England (1978); Oxburgh and Turcotte (1974)). However, our new geochronological constraints on the
timimg of thrusting suggest that erosion was active immediately post-thrusting. Therefore, we use a constant erosion rate of 0.9 mm·a⁻¹ (0.9 km·Ma⁻¹). Shear heating is not considered because the plate interface zone within the Tauern Window is dominated by low-strength carbonate lithologies. Shear heating in these rocks will be negligible above 300 °C as shown by the calculations of Bickle et al. (1975), who calculated shear stress at the base of a 20 km thick overthrust sheet as function of temperature for Yule marble ( Heard, 1963) assuming ductile failure in a 4 km shear zone. Similarly, the effect of syn-metamorphic magmatism or fluid advection are not taken into account as there is no Tertiary igneous activity known from within the Tauern Window; neither are extensive fluid vein networks of the magnitude required by England (1978) observed.

Peak temperature of Tauern Barrovian metamorphism is well constrained by conventional thermodynamic methods to between 500 and 570 °C ( Bickle, 1973; Dachs, 1990; Dachs and Proyer, 2001; Hoschek, 2001) within the south-central Tauern. Variations in temperature estimates from the Schieferhüllle nappes ( Fig. 1) are generally within uncertainty of each other. Pressure estimates are less well constrained due to fewer relevant equilibria and uncertainties in activity–composition relations. We performed average P–T calculations ( THERMOCALC version 3.33, Holland and Powell, 1998) on a metatono Lamarite (TH-519—see Supplemental text S.1 and Table S.D.7) collected from the upper-most levels of the Zentralgneiss ( Fig. 1) within the Großenediger region. Equilibria generated from end-members of garnet, plagioclase, K-feldspar, biotite, muscovite and epidote yield an average pressure of 13.1 ± 2.1 kbar at 601 ± 38 °C (σr = 1.66). Although loosely constrained, the estimate is corroborated by pressures calculated from overprinted calc-schists of the Eclogite Zone, 2–3 km structurally above the Zentralgneiss, ( Hoschek, 2001) between 9 and 10.2 kbar.

Consequently, we consider the range of values for overthrust sheet thickness, radiogenic heat production and mantle heat flow in which conditions of 9–13 kbar and 550 °C are attained in the upper 6 km of the lower-plate within 10 Ma of thrust sheet emplacement.

5.3. Model solutions

5.3.1. Overthrust sheet thickness

We calculate Depth–T–t curves for the basement-top for a range of overthrust sheet thicknesses between 20 and 60 km and a constant mantle heat flow of 27 mW·m⁻² (0.64 HFU). Results are displayed in Fig. 6. The P–T evolution of the upper-basement is characterised by an initial phase of rapid heating (∼2 Ma), driven by equilibration of temperatures across the sawtooth-shaped temperature depression of the plate interface. Subsequent heating is exponentially slower until the basement is exhumed via erosion through colder isotherms. The basement top only attains Tauern temperatures within 10 Ma of overthrusting if the thrust sheet is greater than ~55 km thick. Such a scenario would require peak basement pressures of 14–16 kbar. Peak temperatures for overthrust sheets of 55 and 60 km thickness of 548 °C at 11.2 kbar and 579 °C at 11 kbar respectively, are reached between 20 and 25 Ma post thrusting if rapid exhumation begins after 5 Ma. Interestingly, emplacement of a 30 km thick thrust sheet — the preferred value of Bickle et al. (1975), heats the upper-basement to a peak temperature of 339 °C in 13 Ma ~ 200 °C short of Tauern conditions. For thrust sheets greater than 27 km thickness, erosion must operate more rapidly than 0.9 mm·a⁻¹.

5.3.2. Crustal heat production and mantle heat flow

The temperature attained by the basement-top following 10 Ma conductive heating under a 30 km thick overthrust sheet is plotted against total heat contribution ( A₀·D) from the basement ( Fig. 7). Erosion is not active and mantle heat flow varies between 0.2 and 2.0 HFU (8.36–83.68 mW·m⁻²). Saliently, the calculations show that for Tauern radiogenic heat production values 0.55–1.2 HFU ( Hawkesworth, 1974a,b), Barrovian conditions will only be attained within 10 Ma if mantle heat flow is >62.76–37.66 mW·m⁻² (1.5–0.9 HFU) respectively, at the time of emplacement. Such values of heat flow into the lithosphere correspond to conductive mantle temperature gradients of 25.10–15.06 °C·km⁻¹, implying lithospheric
thinning and asthenospheric upwelling (Sclater et al., 1980). However, helium isotopic ratios within East Alpine groundwaters show a virtual absence of mantle-derived $^3$He ($([^{3}He/^{4}He]_{air}=0.2$, Marty et al., 1992) and there is a notable lack of extensive Alpine magmatism within the Eastern Alps. Both observations are inconsistent with elevated mantle heat flows. In the absence of erosion, these results provide lower-bound estimates as erosion will shorten the time interval over which conductive heating is operative. Erosion would displace the constant mantle heat flow curves of Fig. 8 towards higher temperatures.

5.4. Alternative solutions

5.4.1. Tectonic emplacement

Assuming that the Austroalpine nappes were emplaced ca. 65 Ma, we now consider the scenario in which the Peripheral Schieferhülle nappes (Eclogite Zone, Rote-Wand and Glockner nappes) were tectonically inserted into a heated crustal pile ca. 35 Ma. This end-member tectonic scenario accounts for the lack of petrological evidence that the basement experienced blueschist-facies metamorphism prior to Barrovian conditions, in addition to accounting for the Barrovian metamorphism by conductive heating alone. Fig. 8 shows the thermal evolution of a crustal pile in which a 4 km thick slab is inserted at plate interface depths, into a geotherm produced after 30 Ma of conductive heating beneath a 30 km thick thrust sheet. Initial temperature of the interface depths, into a geotherm produced after 30 Ma of conductive heating 5.4.1. Tectonic emplacement. (Holland and Ray, 1985). All other thermal parameters are as in Fig. 5 except that erosion is not considered due to the short timescales investigated. Given that the thermal time constant ($\tau = a^2/(\pi^2 \kappa)$) of a 4 km slab under such conditions is 0.16 Ma, the slab attains Barrovian conditions rapidly, within ca. 1.2 Ma. However, in order to reconcile tectonic emplacement with eclogitization between 28 and 38 Ma requires subduction to be active for 30 Ma post-emplacement of the Austroalpine nappes at ca. 65 Ma.

5.4.2. Syn-thrusting heating

Oxburgh (1968) suggests that roughly 100 km of displacement has occurred between the Penninic nappes of the southern Tauern Window and the overlying Austroalpine during Alpine convergence. If the maximum duration of thrusting is 10 Ma (38–28 Ma), then thrust sheet emplacement must have occurred at rates greater than 1 cm·a$^{-1}$, akin to plate convergence rates. At high rates of thrusting the upper-basement will experience rapid heating due to the constant replenishment of heat by the allochthonous sheet — effectively maintaining a constant thermal gradient within the upper plate, analogous to the action of a hot iron. However, for this scenario to be plausible, the basement must be located proximal to the inception of thrusting so as to avoid conductive cooling of the thrust sheet. Fig. 9 shows the thermal evolution of a crustal pile undergoing syn-thrusting heating for a thrusting rate of 1 cm·a$^{-1}$. It is clear that syn-thrusting heating would form inverted isotherms within the footwall during early stages of thrusting — as observed in the Himalaya. With subsequent conductive relaxation and radiogenic heat production, footwall isotherms are smoothed and attain similar values to the base of the overthrust sheet within 10 Ma.

Fig. 8. One-dimensional conductive relaxation profile of a 4 km thick slab, collectively representing the Glockner nappe and the Eclogite Zone, inserted into a crustal pile with a geotherm representing 30 Ma post-thrusting (doubling of thickness) conductive heating. The model represents the Eclogite Zone’s insertion into a blueschist facies nappe stack and subsequent heating and exhumation to the upper-greenschist facies, ca. 550 °C (highlighted on P-T path of insert). Time steps are 0.4 Ma duration.

![Fig. 8](image_url)

Fig. 9. The ‘Hot Iron’ scenario. One-dimensional conductive heating of a basement complex with $z_{base}=27$ mW·m$^{-2}$, $A_{base}=5.0$ μW·m$^{-2}$ and $D=8$ km continually over-thrust by a 35 km thick thrust sheet; erosion is neglected; 100 km displacement occurs at 10 km·Ma$^{-1}$ (1 cm·a$^{-1}$). Horizontal distance from inception of thrusting ($L_{base}$) < 39 km. Grey box reflects Tauern metamorphic conditions. Inset plot shows the depth a thermal perturbation (i.e. a sawtooth geotherm of an overthrust sheet) would penetrate against rate of thrusting over 100 km displacement. Graph calculated from thermal time constant relations: $L_{base} = \sqrt{\kappa \cdot \tau_p^3}$ where $L_{base}$ = depth of penetration, $\kappa$ = diffusivity and $\tau_p$ is the time over which the temperature perturbation exists (i.e. duration of thrusting). Grey region delimits the range of basement depths exposed within the Tauern Window.
6. Discussion

A maximum interval of 10 Ma separating thrust sheet emplacement and Barrovian metamorphism in the Eastern Alps raises profound questions over the length scales of heating responsible for regional metamorphism. The classic conductive relaxation model shows that the length scale of conductive heating required to attain peak conditions in < 10 Ma is incompatible with Barrovian pressure estimates and detrital sediment loads (see beneath). Elevated mantle heat flow explains the rapid heating, but lacks supporting geochemical evidence. Tectonic insertion of the Schieferhülle nappes along the plate interface accounts for rapid (<2 Ma) heating from blueschist to Barrovian metamorphic conditions. However, this scenario requires a mechanism to exhume the Eclogite Zone from 70–80 km to ~30 km depth at plate tectonic rates of 1–6 cm·a⁻¹, between ca. 38 Ma and Barrovian metamorphism ca. 27–32 Ma. Similarly, concomitant thrusting and heating explain the <10 Ma timescale of heating, but demand temperatures at the base of the overthrust sheet close to those of peak metamorphism and also a pulse in detrital sediment supply to circum-East Alpine basins.

The Eclogite Zone is bounded by mylonite zones at its contacts with the Gockner and Venediger nappes. The basal contact is characterised by thrust-sense, top-to-the-NNE deformation, whilst its sense of movement relative to the hanging wall is less clear, showing both top-to-the-N and S-side-down pre-syn Barrovian shear indicators. Nevertheless, it is likely that these high strain zones accommodated between 50 and 70 km of displacement during exhumation of the nappe back up the subduction channel, prior to juxtaposing the Eclogite Zone between the basement and Gockner nappes as an extrusion wedge (Behrmann and Ratschbacher, 1989; Glodny et al., 2008). Rapid exhumation of the nappe could have been facilitated by a buoyancy contrast between the subducted crustal material and surrounding mantle (Δρ = 300 kg·m⁻³, England and Holland, 1979), following detachment from the slab (Smye et al., 2010). However, the presence of kilometre-scale stratigraphic continuity in both marbles and quartzite bands of the Eclogite Zone suggests that the nappe was exhumed as a coherent unit (Behrmann and Ratschbacher, 1989). As fluid-assisted granular flow (Stöckhert, 2002) or power–law deformation of aragonite is expected to have controlled the rheology, this raises considerable doubt over whether the transitional crust would be strong enough to support such buoyancy forces throughout 70–80 km exhumation (e.g. Renner et al., 2001). Alternatively, return flow of low viscosity material within a confined subduction channel has been postulated to account for the exhumation of (U)HP rocks (Cloos, 1982; Gerya and Stöckhert, 2006; Gerya et al., 2002; Warren et al., 2008). High viscosity of the subducted margin provides an explanation for the coherent nature of the Eclogite Zone.

Despite plausible exhumation mechanics, insertion of the Eclogite Zone as an extrusive wedge into a heated crustal pile requires that the transition from blueschist to eclogite-facies metamorphism within the Eclogite Zone, Tauern Window. Allanite–clinozoisite grew during the prograde portion rates for the 100 km of displacement between upper and lower plates to ≤ 10 km·Ma⁻¹—similar to rates calculated by Dewey et al. (1989) and Schmid et al. (2004) via plate tectonic and palinspastic restoration respectively. Therefore a range of thrusting rates between 10 and 100 km·Ma⁻¹ is representative of Eocene–Oligocene convergence within the Eastern Alps. Synthrusting heating initially affects the upper-most levels of the basement, forming inverted isotherms which are subsequently smoothed by conductive heating. Fig. 9 shows that synthrusting heating beneath a 30 km thick thrust sheet displaced at rates between 10 and 100 km·Ma⁻¹ could feasibly penetrate the upper 20 km of basement—consistent with Barrovian pressure estimates between 9 and 13 kb calculated from basement rocks.

Overthrusting of a 30 km thick allochthon across the Eastern Alps (1.8×10⁶ km² ~ Oxburgh, 1968) would provide roughly 1.45×10¹⁸ kg of sediment to circum-East Alpine basins in the interval 40 Ma present day, assuming a 10 km present day average thickness of the Austroalpine nappes, a crustal density of 2700 kg·m⁻³ and an average erosion rate of 1.1 mm·a⁻¹. Compared to England (1981)'s estimate of 1.1×10¹⁸ kg for the East Alpine detrital sediment load, this suggests inconsistency between the detrital sediment record and metamorphic pressures, which could be accounted for by a hidden Eocene–present age sediment trap or an overestimate of the metamorphic pressures i.e. a thinner allochthon. The flysch–mélasse transition within circum-Alpine basins occurred across the Eocene–Oligocene boundary (Kuhlemann, 2000; Kuhlemann et al., 2006; Sinclair, 1997), which strongly supports contemporaneous thrust sheet emplacement. Plate velocity overthrusting of the Austroalpine nappes provides an elegant explanation for equally rapid exhumation of the Eclogite Zone as the same basal thrust system would be responsible for both processes (Fig. 10). Similarly, the scenario accounts for continued subduction post-eclogite formation, explaining blueschist facies overprinting prior to Barrovian conditions.

Syntectonic growth of Barrovian assemblages would provide strong evidence in support of footwall heating due to rapid overthrusting of hot rock, as noted in the Lesser Himalaya (Caddock et al., 2007). However, the relationship between Barrovian mineral growth and fabric formation in the Penninic units of the Eastern Alps is less clear. Kurz et al., (1996) state that westward directed shearing initiated synchronous to the Barrovian peak, whilst Droop (1985) and Inger and Cliff (1997) state that the metamorphic peak post-dated regional fabric formation. Furthermore, evidence for Barrovian conditions at the base of the Austroalpine overthrust sheet is lacking; temperatures were high enough to facilitate Ar diffusion in biotite, chloritisation and development of low-temperature quartz microstructures ca. 30 Ma. (Wallis, 1988; Waters, 1976), i.e. ≥ 300–350 °C. Under these conditions, synthrusting heating would not account for the rapid timescales of Barrovian metamorphism. However, due to the heavily reworked and anhydrous nature of the polymetamorphic basement to the Austroalpine nappes (the Altkristallin; e.g. Siegesmund et al., 2007), it is uncertain whether pervasive development of Barrovian mineralogy would occur under higher grade conditions, particularly given the short timescales of heating.

In the absence of an advective component to heating, syn-thrusting heating provides a theoretical explanation for the rapid (~10 Ma) tectono-metamorphic evolution of the Eastern Alps, but lacks directly supporting field evidence. Tectonic replenishment of heat to footwall units may be a fundamental mechanism to other overthrust terranes, such as the Himalaya, where syn-kinematic Barrovian assemblages are observed.

7. Conclusions

1. We present the first U–Pb geochronological evidence for the age of eclogite-facies metamorphism within the Eclogite Zone, Tauern Window. Allanite–clinozoisite grew during the prograde portion
of the Eclogite Zone’s P–T–t path, between 8 and 13 kbar at 34.2 ± 3.6 Ma, prior to initiation of garnet growth. Combined with previously reported Barrovian metamorphism at 27–32 Ma, this places a maximum 10 Ma period between ~28 and 38 Ma during which the peak of East Alpine eclogite-facies metamorphism occurred. Eclogites facies rocks were exhumed at plate velocity rates, between 1 and 6 cm·a⁻¹, over a vertical distance of ~50 km.

2. These new geochronological data drastically shorten the duration of time available for conductive relaxation of isotherms following thrust sheet emplacement, from ~30 Ma to ≤10 Ma. We show that the thermal evolution of the Tauern Window cannot be explained by conductive heating of overthickened crust on lithosphere with normal continental thermal gradients. Either the thermal evolution took place with a significant thermal contribution from the mantle, for which there is little supporting evidence or heating occurred during thrusting with heat provided by an overlying thrust sheet. It is possible that syn-thrusting heating by rapid emplacement of a hot overthrust sheet, overlooked in previous thermal models, could plausibly have played an influential role in the tectono-metamorphic evolution of the Eastern Alps and in overthrust terrains in general.

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References


Fig. 10. Tectonic schematic of scenario in which concomitant syn-thrusting heating of the Penninic basement and plate velocity exhumation of the Eclogite Zone occur. This is possible because the same basal thrust is responsible for the rates of both thrust sheet emplacement and exhumation. Isotherms are approximate and represent an early thermal architecture associated with oceanic subduction. Continental collision would raise isotherms to shallower crustal levels.


