Exhumation as fast as subduction?

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ABSTRACT

We produced a pressure-temperature-time path in order to determine the exhumation rate of the deepest subducted Alpine rocks. In situ dating of peak-metamorphic titanite in an eclogite facies calc-silicate rock indicates that subduction to pressures of ~3.5 GPa was reached at 35.1 ± 0.9 Ma. Titanite formed during two decompression stages, at 1 ± 0.15 GPa and ~0.4–0.5 GPa, and yielded ages of 32.9 ± 0.9 Ma and 31.8 ± 0.5 Ma, respectively. Combining the age data and making assumptions about the conversion of pressure to depth yield mean exhumation rates of 3.4 cm/yr and 1.6 cm/yr. These rates imply that exhumation acted at plate tectonic speeds similar to subduction, and was significantly faster than erosion. We suggest that fast exhumation is driven by a combination of tectonic processes involving buoyancy and normal faulting.

Keywords: titanite, exhumation, high-pressure metamorphism, U/Th/Pb, geochronology, Western Alps.

INTRODUCTION

The occurrence of high-pressure (*P*) rocks within orogenic belts provides evidence for the dynamic Earth processes of subduction and exhumation of crustal material. The exhumation mechanism of deeply buried rocks remains unclear, and any model (England and Holland, 1979; Ernst et al., 1997; Liou et al., 1997; Michard et al., 1993; von Blanckenburg and Davies, 1995) is dependent on the rate of this process. Although subduction rates are well known from plate tectonic reconstruction to be 1–10 cm/yr, determination of exhumation rates can only be deduced from the pressure-time (*P-t*) history of high-*P* rocks. So far, the dating of high-*P* terranes has been limited by major problems. (1) Metamorphic rocks generally display a polyphase evolution; therefore, dating of multigrain fractions or even single grains often produces mixed ages. (2) Most isotopic systems in metamorphic minerals do not record the time of formation, but rather date the time of isotopic closure during cooling (Dûchene et al., 1997; Monié and Chopin, 1991), the temperature (*T*) of which is not precisely known. In addition, ultrahigh-pressure rocks cool only slightly during exhumation; consequently, it is nearly impossible to obtain detailed *P-t* information by using such isotopic systems. (3) In situ U-Pb dating of zircon and monazite avoids these problems, but is limited by the difficulty of deciphering the link between the determined age and metamorphic conditions. (4) Dating of the ultrahigh-*P* metamorphic mineral phengite is problematic because it is often contaminated by excess argon; such contamination prevents meaningful age determination (Kelley et al., 1994).

We tackled the problem of exhumation-rate determination by marrying metamorphic petrology to geochronology to allow dating of titanite that formed at different *P-T* conditions. To avoid mixing ages, we used the sensitive high-resolution ion microprobe (SHRIMP) to date in situ, directly in thin section, the single growth zones of titanite grains. The resistance of the U-Pb system to high temperature resetting ensured the measurement of formation ages. Moreover, the growth zones of titanite contained mineral inclusions that could be linked to the paragenesis of the host rock and thus to metamorphic conditions. We investigated Tertiary high-*P* rocks, the young age of which makes it possible to resolve rates of fast geologic processes with precise dating.

GEOCHRONOLOGY OF METAMORPHISM

We analyzed two calc-silicate nodules in marbles from the ultrahigh-*P* Western Alps unit of the Dora Maira, a coherent body of continental crust consisting of a heterogeneous basement (metapelites with intercalated eclogites, calc-silicate rocks, and marbles) that was intruded by Permian-Carboniferous granites (Chopin et al., 1991; Compagnoni et al., 1995; Michard et al., 1993). There is evidence through the whole unit of a widespread recrystallization in the coesite stability field during the Alpine orogeny at pressures of ~3.5 GPa and temperatures of ~750 °C (Chopin et al., 1991; Compagnoni et al., 1995; Schertl et al., 1991).

The first sample contains a clear eclogite facies paragenesis with garnet and omphacite (Jd_{38}; Fig. 1A; Table 1) and only minor retrogression. Titanite is part of the ultrahigh-*P* paragenesis, as indicated by equilibrium textures with omphacite and garnet and local occurrence of inclusions of omphacite and rutile (Fig. 2A). Calculated temperatures from garnet and omphacite in the calc-silicate rock, as well as from garnet and phengite in

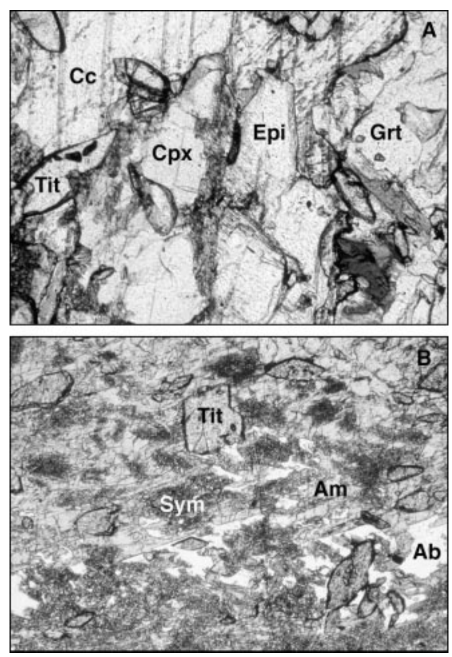

Figure 1. Photomicrographs of dated (A) ultrahigh-pressure and (B) low-pressure calc-silicate rock. Ab—albite; Am—amphibole; Cc—calcite; Cpx—clinopyroxene; Epi—epidote; Grt—garnet; Sym—symplectite of clinopyroxene and/or amphibole + plagioclase; Tit—titanite. Base of pictures is 3 mm wide.

TABLE 1. DOCUMENTED METAMORPHIC STAGES AND CHARACTERIZATION OF MINERALS IN THE ANALYZED CALC-SILICATES

Mineral	Pre-Alpine	Ultrahigh pressure	Decompression	Epidote-amphibolite
Calcite				
Garnet	?	Py_8; Alm_{53}; Gro_{37}	?	Py_5; Alm_{44}; Gro_{51}
Clinopyroxene	?	Jd_{38}; Ac_4; Mg# 0.72	Jd_{20}; Ac_0; Mg# 0.75	Jd_6; Ac_0; Mg# 0.65
Epidote	?	Epi_{45}		Epi_{55}
Titanite	Al-tit_5	Al-tit_{10}	Al-tit_{14}	Al-tit_9
Rutile				
Amphibole	?		Tschermakite	Hornblende
Plagioclase	?		An_{15}	An_8

Note: Compositions are given in percentages of end members. Py—pyrope; Alm—almandine; Gro—grossular; Jd—jadeite; Ac—acmite; Epi—epidot; Al-tit—aluminium bearing titanite; An—anorthite; Mg#—Mg/(Mg + Fe^{2+}).

the surrounding metapelites, are compatible with the reported peak temperature for the ultrahigh-*P* unit (Fig. 3A). Calculation of the equilibrium pyrope + 6 titanite → 6 rutile + grossular + 3 diopside (equilibrium 1) is in agreement with stability of titanite under ultrahigh-*P* conditions (Fig. 3A). In situ U-Th-Pb measurements with SHRIMP of the ultrahigh-*P* titanite (12 grains; Table 2[1]) yielded a Th/U ratio of 1.5–2.2 and a mean age of 35.1 ± 0.9 Ma (Fig. 2, A and C). The 12 grains analyzed show no difference in age according to dimension. A few titanite cores with lower Al contents and higher Th/U ratios (2.1–8.1) had apparent U-Pb ages that scattered between 253 and 87 Ma (Table 2; Fig. 2, A and C). These cores most likely formed during pre-Alpine metamorphism and then lost part of their radiogenic Pb during Alpine metamorphism, leading to geologically meaningless U-Pb ages. However, the presence of inherited radiogenic-Pb components indicates that the rock never remained at high-*T* long enough to allow complete resetting of the U-Th-Pb isotopic system in the titanite cores. Therefore, the Alpine age dates the formation of the titanite and not the closure of the isotopic system during cooling. Applying the Pb diffusion data of Cherniak (1993) to the inherited cores, it can be deduced that the Dora Maira titanites (<200 μm; Fig. 2) remained above 700 °C for only a fraction of a 1 m.y.

[1]GSA Data Repository item 20015, Table 2, U-Th-Pb analyses, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org or at www.geosociety.org/pubs/ft2001.htm.

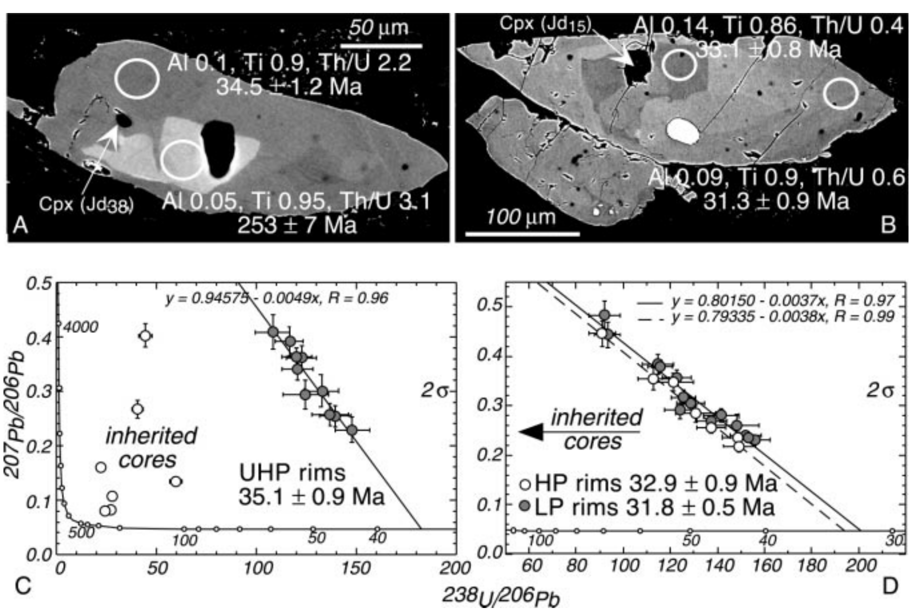

Figure 2. Titanite analyses and geochronology. Backscattered-electron images of titanite crystals from (A) ultrahigh-pressure (UHP) and (B) low-pressure calc-silicate rock. Circles represent sensitive high-resolution microprobe analysis pits for which single ages (±1 σ) and Al-Ti contents (per formula unit) are given. Tera-Wasserburg (1972) diagrams plot uncorrected U-Pb data for titanite from (C) UHP calc-silicate rock and (D) low-pressure calc-silicate rock.

Widespread symplectites of pyroxene and/or amphibole + plagioclase after omphacite (Fig. 1B) demonstrate that the second sample dated was strongly recrystallized during decompression. Relicts of garnet and omphacite (Jd_{40}), similar to the main minerals in the ultrahigh-*P* calc-silicate, provide evidence that both samples shared the same evolution. A first symplectite stage involves omphacite (Jd_{20}) coexisting with oligoclase (Table 1). Maximum pressures of this stage can be calculated by the equilibrium 2, albite → jadeite + SiO_2. Because no free quartz is present, the calculated equilibrium reflects a maximum pressure of ~1.2 GPa for the decompression stage. This first major retrogression most likely occurred at 1 ± 0.15 GPa (35 ± 5 km) during nappe stacking in the Dora Maira (Michard et al., 1993). The coexistence of tschermakite and oligoclase is compatible with lower amphibolite facies conditions (~550 °C).

That Na-poor diopside (Jd_6) and albite were stable during a second symplectite stage indicates pressures <0.5 GPa according to equilibrium 2. The observed paragenesis (Fig. 1B; Table 1) indicates metamorphism in the epidote-amphibolite facies, i.e., ~0.4–0.5 GPa (~17 km) and ~550 °C. Similar conditions have been documented in several Penninic units of the Western Alps (Borghi et al., 1996).

There are three titanite generations in the second sample, and they have distinct textural and chemical features (Fig. 2B; Table 2; see footnote 1). Rare cores with Al-Th-U compositions and ages similar to those of the pre-Alpine titanite cores in the ultrahigh-*P* sample are present. Domains with higher Al contents and low Th/U ratios (0.8–0.5) locally contain inclusions of omphacite ($Jd_{10–20}$, Fig. 2B) and thus formed during the decompressional stage. The mean age of this titanite generation (32.9 ± 0.9 Ma, Fig. 2D) is only 2.2 m.y. younger than the titanite formed at the ultrahigh-*P* peak. A third titanite generation has lower Al contents and forms the rims that are in textural equilibrium with the epidote-amphibolite facies paragenesis. A mean age of 31.8 ± 0.5 Ma was obtained (Fig. 2D) for this titanite.

DISCUSSION

The link between the high-precision U-Pb data on titanite and the metamorphic stages permits us to define a *P-T-t* path that describes the evolution of the Dora Maira from subduction to exhumation (Fig. 3). This path was constructed by dating in situ the same mineral formed at different *P-T* conditions in one rock type, using a single technique. This approach eliminates the problem of comparing ages ob-

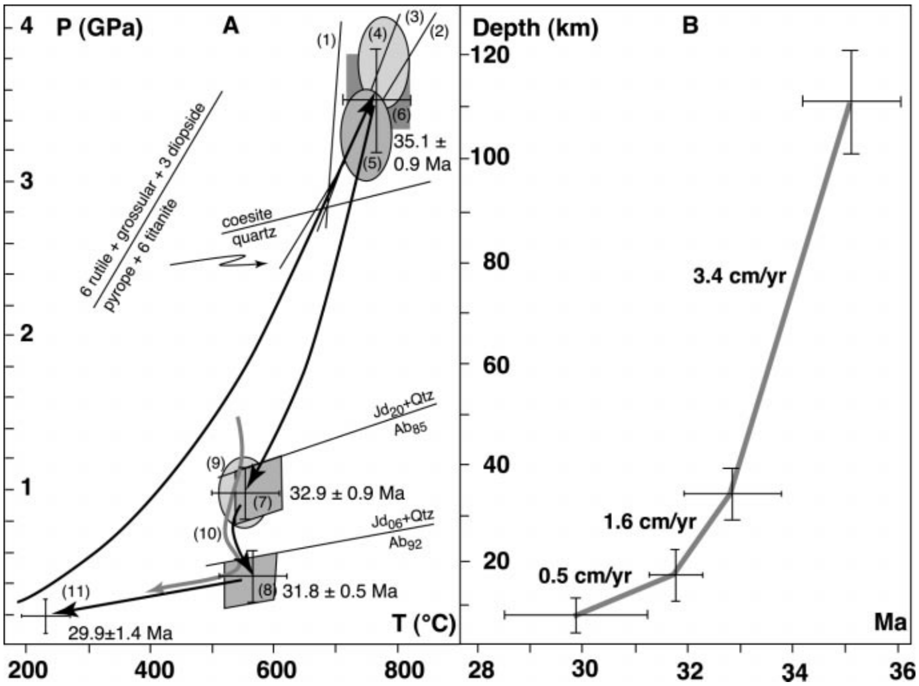

Figure 3. A: Pressure-temperature-time (*P-T-t*) path of Dora-Maira ultrahigh-pressure (UHP) unit. UHP conditions. (1) Garnet-clinopyroxene Fe-Mg thermometer (Ellis and Green, 1979) with Fe^{3+} = Na-Al for dated calc-silicate rock. (2) Equilibrium 1 in calc-silicate calculated by using thermodynamic database (Berman, 1988), activity models for diopside (Holland, 1990), pyrope and grossular (Hodges and Royden, 1984), and ideal mixing for titanite. (3) Garnet-phengite Fe-Mg thermometer (Green and Hellman, 1982) in country rocks of calc-silicate. Peak conditions are deduced from rock types that are part of same structural package with calc-silicates. (4) K-bearing whiteschists (Schertl et al., 1991). (5) Na-bearing whiteschists (Compagnoni et al., 1995). (6) Phengite-eclogites (Nowlan et al., 2000). Peak *P-T* value represents mean of our and literature data with 2 σ errors. Retrogression: (7, 8) *P-T* estimates for two retrogression stages derived from calculation of equilibrium 2 (database from Berman, 1988; activity models: jadeite [Holland, 1990], albite [Holland and Powell, 1992]) and observed parageneses in calc-silicate rocks. (9) Retrogression common to UHP unit and neighboring units (Michard et al., 1993) indicating conditions of nappe stacking. (10) *P-T* evolution of internal Penninic nappes in Western Alps according to Borghi et al. (1996), who documented slight temperature increase during second stage of decompression. Error bars on *P-T* values for two retrogression stages are drawn to include all reported estimates. (11) *P-T* conditions deduced from closing temperature of zircon fission tracks and assuming typical postcollisional geotherm of 35 °C/km (Schlunegger and Willett, 1999) resulting in pressures of 2 ± 1 kbar. Fission-track age is from Gebauer et al. (1997). B: Depth vs. time path from which mean exhumation rates are calculated. Conversion from pressure to depth was calculated by assuming 20-km-thick upper crust, 10-km-thick lower crust followed by upper mantle with densities of 2.7, 3.0, and 3.3 g/cm³, respectively. In this model minimum crustal thickness of 30 km is assumed because subduction of Dora Maira unit occurred before continental collision. Any increase in crustal thickness would lead to slight increase in subduction depth and hence to higher exhumation rates. Deviation from lithostatic pressure by possible tectonic overpressure is considered to be smaller than errors at peak UHP conditions (3.5 ± 0.3 GPa).

tained with different techniques on various rock types and potentially having different age biases (e.g., Chopin et al., 1991; Dûchene et al., 1997; Gebauer et al., 1997). The *P-T-t* path gives a detailed picture of exhumation of ultrahigh-*P* rocks and permits insight into the dynamics of this important geologic process.

There has been a long debate on the age of ultrahigh-*P* metamorphism in the Dora Maira. The first radiometric age determinations pointed to a Cretaceous age (Hunziker et al., 1992; Monié and Chopin, 1991), whereas several contributions argued for a much younger, late Eocene to early Oligocene ultrahigh-*P* metamorphism (Dûchene et al., 1997; Gebauer et al., 1997; Tilton et al., 1991). Our data strongly support the latter hypothesis.

If we assume lithostatic pressure and a layered lithosphere (see Fig. 3 caption), the 3.5 ± 0.3 GPa documented in the ultrahigh-*P* paragenesis indicates subduction to 110 ± 10 km depth. The ultrahigh-*P* rocks of the Dora Maira unit were exhumed very quickly, from 110 ± 10 (35.1 ± 0.9 Ma) to 35 ± 5 km depth (32.9 ± 0.9 Ma) with a mean exhumation rate of 3.4 cm/yr (34 km/m.y.; Fig. 3B). A minimum estimate, which considers the errors bars on ages and pressures, would still give an exhumation rate of 1.5 cm/yr. However, this minimum rate is unlikely considering the entire depth versus time path (Fig. 3B). Subsequently, the exhumation of the Dora Maira slowed and proceeded at mean rates of 1.6 cm/yr to ~17 km depth. The best evidence for the postcollisional evolution of the Dora Maira comes from zircon fission-track data, which indicate cooling to ~250 °C at 29.9 ± 1.4 Ma (Gebauer et al., 1997). The fission-track data imply that the late exhumation of the Dora Maira proceeded at a slower rate of 0.5 cm/yr (Fig. 3B). These data are consistent with the $^{39}Ar/^{40}Ar$ dating of biotite formed during greenschist facies overprint, which points to cooling below ~350 °C ca. 30–32 Ma (Monié and Chopin, 1991). Our study results agree with data from Gebauer et al. (1997), who inferred exhumation of 2.2 cm/yr on the basis of a SHRIMP U-Pb zircon age of 35.4 ± 1.0 Ma and fission-track data. However, these authors assumed a linear trend between the ultrahigh-*P* and the fission-track ages and could not resolve the possible changes in exhumation rates at different crustal levels reported here.

Cooling of the rocks during decompression suggests exhumation at the top of a cold, downgoing slab. Assuming subduction at 45°, the mean velocity of the ultrahigh-*P* rocks would be ~5 cm/yr to achieve exhumation at 3.4 cm/yr. This velocity is only comparable to fast plate motion and thus is significantly faster than convergence between Europe and Africa in the Eocene-Oligocene (1 cm/yr; Dercourt et al., 1986). At that time, erosion in the Alpine area was ~0.25–0.5 mm/yr (Schlunegger and Willett, 1999), and even the fastest erosion documented on Earth (1.5 cm/yr; Ring et al., 1999) could not account alone for the exhumation of the Dora Maira to the base of the crust. Therefore, the fast exhumation from 110 to 35 km depth probably resulted from the interplay of tectonic processes. The strong buoyancy of continental rocks at mantle depth was the most likely driving force for exhumation (England and Holland, 1979; Ernst et al., 1997; Liou et al., 1997). Slab break off might have simultaneously removed dense eclogites (von Blanckenburg and Davies, 1995), which had originated in the previously subducted oceanic crust, and thus enhanced fast exhumation of the remaining, less dense material. During the first stage of exhumation, internal deformation was limited as pre-Alpine intrusive contacts are still preserved in the ultrahigh-*P* unit (Compagnoni et al., 1995). Consequently, deformation during exhumation was likely concentrated in a thrust zone at the bottom and a normal fault on top of the unit. At 32.9 ± 0.9 Ma and 35 km depth, the ultrahigh-*P* lens was stacked together with other units and nappes produced by the continental collision between Africa and Europe. Normal faults overprinting the nappe stack (Philippot, 1990) provide evidence that tectonic exhumation may have contributed significantly to the still-fast exhumation (1.6 cm/yr) to mid-crustal levels (~17 km). Apparently, up to this stage, fast exhumation was not associated with fast erosion, because sedimentation of conglomerates in the Alpine molasse is documented only after the middle Oligocene (Trümpy, 1980). The onset of conglomerate sedimentation was probably contemporaneous with the slowing of exhumation to 0.5 cm/yr, which could have been accommodated by the fast rise of the Alps concomitant with intensive erosion.

APPENDIX. METHODS

SHRIMP data acquisition and reduction were similar to the methods used for zircon (Compston et al., 1992). The analyses were performed on thin sections; as a consequence, they had a relatively high percentage of common Pb, resulting from a mixture of surface common Pb and common Pb naturally contained in titanite. For each of the three data populations, the common $^{207}Pb/^{206}Pb$ ratio was obtained from the regression line through the data points. This ratio was then used to correct the data by assuming concordance according to Compston et al. (1992). The low initial $^{207}Pb/^{206}Pb$ ratio determined in two younger titanite generations implies that a small percentage of radiogenic Pb was incorporated in the titanite at the time of formation. Mean ages are given at 95% confidence level.

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