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Dating the initiation of Piemonte-Liguria Ocean subduction: Lu–Hf garnet chronometry of eclogites from the Theodul Glacier Unit (Zermatt-Saas zone, Switzerland)

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Abstract The Penninic nappe stack in the Central and Western Alps was formed in a collision zone environment after the closure of the Penninic oceans in the Paleogene. This study reports Lu–Hf garnet-whole rock ages of 56.5 ± 2.7 and 58.2 ± 1.4 Ma for two eclogite samples from the Theodul Glacier Unit, which is inserted within the structurally uppermost parts of the ophiolitic Zermatt-Saas Zone. The distribution of major elements, Mn, Y, and Lu in garnet, and specifically an enrichment of Lu in the cores, indicate that the ages record prograde growth of garnet during pressure increase. They provide direct evidence for the continuation of subduction during the "Paleocene restoration phase", often regarded as a tectonically quiescent period due to a reduction in clastic sediment deposition, lack of folds and thrusts of this age, and a cessation of Africa–Europe convergence as derived from the magnetic anomaly pattern in the Atlantic Ocean. The evidence for ongoing subduction in the absence of Africa–Europe convergence suggests that the subduction system was driven by gravity acting on the downgoing slab in a rollback setting, and that subduction was balanced by extension of the upper plate. The overlap of the Lu–Hf ages of both samples from the Theodul Glacier Unit show that this tectonic element represents a coherent body. The difference with respect to the 48 Ma Lu–Hf age of the Lago di Cignana Unit, another element of the Zermatt-Saas Zone, shows that the Zermatt-Saas Zone consists of tectonic subunits, which reached their respective pressure peaks over a prolonged period of approximately 10 Ma.

Keywords Lu–Hf garnet geochronology · Eclogite · Trockener Steg · Swiss Alps · Zermatt-Saas zone

1 Introduction

The Western and Central Alps represent a classical arc-shaped orogen assembled by subduction and collision. Tectonic models that attempt to reconstruct their evolution (e.g., Laubscher 1988, 1991; Schmid et al. 1996; Michard et al. 1996; Escher et al. 1997; Schmid and Kissling 2000; Stampfli et al. 1998, 2002; Rosenbaum and Lister 2005; Handy et al. 2010) showed that the deformation and metamorphism migrated from internal to external parts, that is, mostly towards northwest. It is not clear to what extent this migration was continuous or episodic (Lister et al. 2001). Trümpy (1973) found that the Cretaceous deformation, mostly recorded in the Austroalpine nappes, did not simply continue into the Eocene to Oligocene main deformation phases of the Central and Western Alps but that the two were separated by a period of relative tectonic quiescence, uplift and erosion during the Paleocene, i.e., 65–56 Ma ("Paleocene restoration"; Trümpy 1973; Schettino and Turco 2011). Later, the analysis of plate motions from magnetic anomaly patterns in the Atlantic showed that the rate of Europe-Africa convergence at the longitude of the Alps was only c. 0.22 cm $year^{-1}$ between

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65 and 55 Ma and c. 0.4 cm year^{-1} between 55 and 51 Ma (Schmid et al. 1996, using rotation parameters of Dewey et al. 1989; see also Rosenbaum et al. 2002; Jolivet et al. 2003; Rosenbaum and Lister 2005; Schettino and Turco 2011). Convergence rates were considerably higher before and after this period. This slow-down of convergence coincides with the "Paleocene restoration". So far, the geochronological record for subduction-related metamorphism also shows a gap between c. 65 and c. 50 Ma (see below). This may indicate that subduction stopped at that time. However, using semi-quantitative profile balancing, Schmid et al. (1996) derived significantly higher convergence rates across the Alps of 1.33 cm year^{-1} for 65–50 Ma, and assumed continuing subduction during the Paleocene. In order to better constrain the subduction history of the Central and Western Alps, and to answer the question of continuous versus discontinuous subduction, more geochronological data for high-pressure units are needed.

The Penninic nappe stack of the Western and Central Alps (Fig. 1) consists of both oceanic and continental units subducted to various depths, which were then juxtaposed together and subsequently exhumed to the surface. This is reflected by a large spectrum of mineral assemblages, which developed under low-temperature/high-pressure conditions and afterwards were overprinted by Barrovian-type metamorphism (Bearth 1967; Reinecke 1991; Dal Piaz 1999; Bousquet et al. 2004; Bucher et al. 2005; Frezzotti et al. 2011; Gasco et al. 2013). The eclogite-facies mineral assemblage is extensively preserved in the Sesia zone, in the ophiolites and continental outliers of the Zermatt-Saas Zone (ZSZ), in the structurally deeper Antrona and Balma ophiolites, and in the "Internal Massives" of Monte Rosa, Dora-Maira and Gran Paradiso (Fig. 1).

The ZSZ, one of the most intensively studied subducted ophiolite complexes worldwide, has been investigated in numerous works by various geochronological methods (e.g., Bowtell et al. 1994; Rubatto et al. 1998; Amato et al. 1999; Dal Piaz et al. 2001; Lapen et al. 2003). These dating techniques constrain the timing of formation and subduction of the Piemonte-Liguria Ocean. Although the ZSZ has received a lot of attention during the past years, most geochronological studies dealt with only a few localities. U–Pb zircon, Sm–Nd garnet, and Lu–Hf garnet data for the subduction-related metamorphism exist only for the ultra-high-pressure (UHP) locality Lago di Cignana (Fig. 1: LDC; Rubatto et al. 1998; Amato et al. 1999; Lapen et al. 2003), the locality Pfulwe further north (Fig. 1; Bowtell et al. 1994), and the Monviso ophiolite further south (Duchêne et al. 1997; Cliff et al. 1998; Rubatto and Hermann 2003). However, the ZSZ is a complex, about 60 km long, dismembered ophiolite sequence including also rock slivers of continental affinity (Fig. 1: continental outliers). Some authors suggested that these continental slivers were emplaced as extensional allochthons already during pre-oceanic rifting (Dal Piaz et al. 2001; Beltrando et al. 2010) and that the ZSZ was subducted and exhumed in one piece (e.g., Angiboust et al. 2009), whereas others assumed that it is composed of several tectonic slices with independent metamorphic histories (e.g., Negro et al. 2013). The geochronological record is still not sufficient to distinguish between these alternatives. In this article, we present two new age determinations from the Theodul Glacier Unit (TGU) in the Zermatt-Saas Zone, a unit that has not been dated so far.

In early works, the ^{40}Ar-^{39}Ar technique was used to date high-pressure metamorphic events in the Western and Central Alps (e.g., Chopin and Maluski 1980; Monié and Chopin 1991; Hunziker et al. 1992) but it has been shown that ^{40}Ar-^{39}Ar ages of high-pressure rocks are often affected by the presence of excess argon, making them too old (Li et al. 1994; Arnaud and Kelley 1995; Ruffet et al. 1997; Warren et al. 2012). Rb–Sr isochrons from phengitic mica (Paquette et al. 1989; Ruffet et al. 1997; Dal Piaz et al. 2001) are unaffected by this problem and date the high-pressure metamorphism provided that the closure temperature of the Rb–Sr system in white mica (c. 500 °C ± 50; Jäger 1979; Inger and Cliff 1994) was not exceeded (Dodson 1973; Ganguly and Tirone 1999; de Meyer et al. 2014).

U–Pb zircon geochronology has the advantage of a high closure temperature and the possibility of single spot dating using SHRIMP or LA-ICPMS. In mafic lithologies of ophiolites, however, zircon is rare. Furthermore, it is often difficult to correlate the growth or recrystallization of zircon to a certain step of the P–T evolution (Rubatto et al. 2001; Hermann et al. 2001; Rubatto 2002; Rubatto and Hermann 2007). In spite of these problems, U–Pb dating of metamorphic zircon domains has been successfully applied in the Western and Central Alps (Tilton et al. 1991; Gebauer et al. 1992, 1997; Gebauer 1996, 1999; Rubatto and Gebauer 1999; Rubatto et al. 1999; Rubatto and Hermann 2003; Liati et al. 2003, Hermann et al. 2006).

Garnet can be dated by the ^{147}Sm to ^{143}Nd and ^{176}Lu to ^{176}Hf decay systems, where the Lu–Hf chronometer seems to be the more suitable system to date prograde metamorphism in eclogite rocks due to the higher closure temperature (Duchêne et al. 1997; Ganguly and Tirone 1999; Schmidt et al. 2011; Herwartz et al. 2008, 2011; Kirchenbaur et al. 2012; Nagel et al. 2013; Smit et al. 2013). Moreover, the Lu–Hf garnet-whole rock ages are affected by epidote-zoisite-phosphate inclusions only to a minor extent when compared to the Sm–Nd system (Zhou and Hensen 1995). The only critical types of inclusions are zircon and rutile. Their high Hf content can strongly influence the Lu–Hf system (Scherer et al. 2000). This

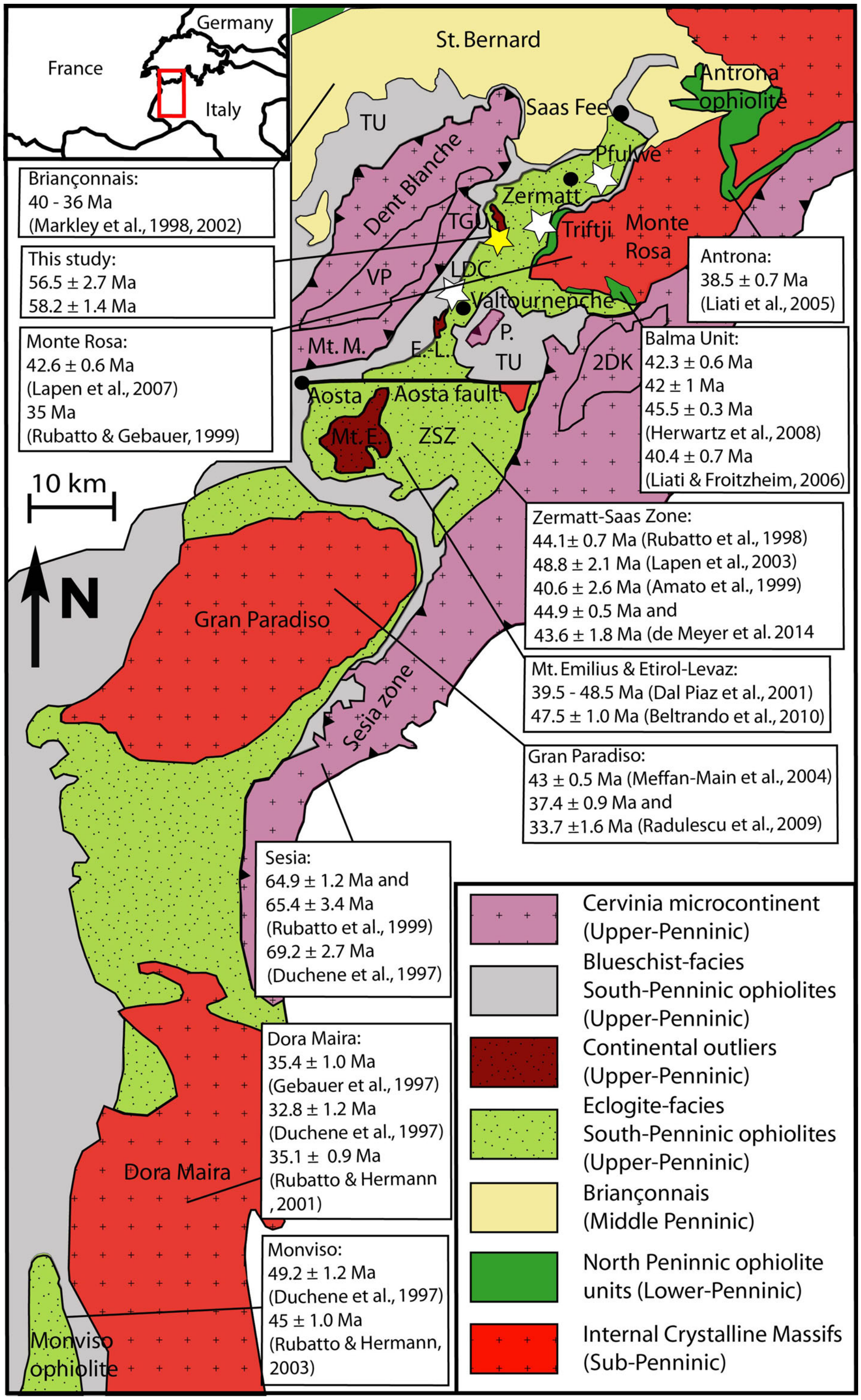

Fig. 1 Tectonic map of the Western Alps, showing distribution of HP ages for metamorphic rocks (modified after Rosenbaum and Lister 2005). White stars indicate the location of Pfulwe pass area, where eclogite facies rocks preserved pillow textures, the Triftji locality at the base of the Breithorn, and the Lago di Cignana coesite locality (LDC). Dent-Blanche nappe, Sesia zone and Pillonet klippe are considered as derived from the Cervinia microcontinent. Although the continental outliers were probably also part of Cervinia, they are designated as a separate unit. *TGU* Theodul Glacier Unit, *LDC* Lago di Cignana Unit, *E. L.* Etirol-Levaz sliver, *Mt. E.* Mont Emilius, *Mt. M.* Mont Mary, *P.* Pillonet klippe, *VP* Valpelline Series, *2DK* Seconda Zona Dioritico-Kinzigitica

problem can be minimized by the selective dissolution procedure for garnet of Lagos et al. (2007).

The aim of this contribution is to present Lu–Hf isotope data for whole rocks and garnet mineral separates for two eclogite samples belonging to the TGU. The Lu–Hf data are combined with element mapping of single garnet grains, in order to correlate the age information with the metamorphic path. By using the TGU as a case study, the present geochronological results contribute to discussing the following questions:

1. Was subduction in the Alps continuous or episodic?

2. What is the significance of plate tectonics for the Paleocene restoration?
3. Was the Zermatt-Saas Zone subducted in one piece or is it a composite of units subducted at different times?

2 Regional geological setting and previous dating

The western Alpine orogenic wedge consists of a sequence of continental and ophiolitic thrust sheets which are aligned parallel to the main strike of the Alpine orogen. From the base to the top, the following structural domains can be subdivided: (1) the European margin, represented by tectonic units of the Helvetic nappes, Dauphinois, External Crystalline Massives (e.g., Aiguilles Rouges, Montblanc), and Internal Crystalline Massives (Monte Rosa, Gran Paradiso and Dora Maira) (Gebauer 1999; Froitzheim 2001), (2) units from a northern ocean basin, the Valais Ocean (Lower Penninic Nappes) (Liati et al. 2003, 2005; Liati and Froitzheim 2006), (3) the St. Bernard multi-nappe system derived from the Briançonnais continental zone (Middle Penninic nappes) (Frisch 1979; Stampfli et al. 1998), (4) units from the southern ocean basin, the Piemonte-Liguria Ocean (Upper Penninic nappes) (Rubatto et al. 1998; Dal Piaz et al. 2001; Bousquet et al. 2004), and (5) units from the Cervinia Microcontinent (Pleuger et al. 2007) or Margna-Sesia Fragment (Schmid et al. 2004), represented by the Sesia Zone, Dent-Blanche Nappe, Mt. Mary, and Pillonet Klippen (Upper Penninic Nappes) (Fig. 1). In addition, small fragments, which show lithological and metamorphic features similar to those of the Sesia Zone, occur between the different Upper Penninic ophiolite units (Ballèvre et al. 1986). All nappes have been thrust towards NW over the Molasse Basin and European basement and record a decrease in metamorphic grade from SE to NW (Berger and Bousquet 2008).

Apart from the Internal Crystalline Massifs, the European domain is overprinted by sub-greenschist to greenschist-facies metamorphism without any evidence for a HP metamorphic imprint (Frey et al. 1999). The origin of the Internal Crystalline Massifs is still a matter of debate (Fig. 1). They are considered to derive from continental crust of the Briançonnais terrane (Escher et al. 1997; Schmid and Kissling 2000; Schmid et al. 2004), from the Adria domain (Stampfli et al. 1998), or from the distal margin of Europe (Sub-Penninic nappes; Gebauer 1999; Froitzheim 2001). We follow the latter interpretation because it is in line with the young ages of HP/UHP metamorphism in these units (see below). In the case of the Dora-Maira Massif, the presence of coesite indicates UHP metamorphism at depths of more than 100 km (Chopin 1984), dated around 35 Ma (Duchêne et al. 1997; Gebauer 1999). A U–Pb rutile age for eclogite-facies metamorphism in the Monte Rosa nappe is 42.6 ± 0.6 Ma (Lapen et al. 2007). The eclogite-facies imprint of the Gran Paradiso nappe was dated at 43.0 ± 0.5 Ma using Rb–Sr on apatite and phengite (Meffan-Main et al. 2004), but this result was called into question by Radulescu et al. (2009) who interpreted 37.4 ± 0.9 and 33.7 ± 1.6 Ma (U–Pb SHRIMP on monazite and allanite, respectively) as dating the high-pressure metamorphism.

Within the Lower Penninic Nappes (Valais Ocean), the subduction history is relatively weakly constrained because they are flysch-dominated with minor intercalated ophiolitic material (Ziegler 1956; Trümpy 1980; Coward and Dietrich 1989). Published radiometric ages for the Antrona ophiolite and the Balma Unit, which are assigned to the Valais Ocean using structural arguments (Froitzheim 2001), yielded 40–37 Ma for the high-pressure metamorphism (Liati et al. 2003, 2005; Liati and Froitzheim 2006). Herwartz et al. (2008) dated garnet growth in the Balma Unit at 45–40 Ma using Lu–Hf garnet geochronology.

The Briançonnais high consists of pre-Mesozoic continental basement with a sedimentary cover. Paleogeographic reconstructions for the Cretaceous generally consider it as the eastern prolongation of Iberia, separating Valais and Piemonte-Liguria Ocean basins (Stampfli et al. 1998; Schmid et al. 2004). The Briançonnais nappes display an Alpine metamorphism grading eastward from HP greenschist facies to blueschist facies (Bearth 1963; Goffé 1977; Bucher et al. 2003; Oberhänsli et al. 2004; Bousquet et al. 2004; Bucher and Bousquet 2007). The Briançonnais reached peak pressure conditions during the Middle Eocene between 50 and 43 Ma as indicated by Ar/Ar data on HP-phengites (Markley et al. 1998, 2002).

The Zermatt-Saas Zone and other equivalent units further south (e.g. Monviso Ophiolite) comprise eclogite-facies metamorphosed ophiolites. They derived from the Middle to Late Jurassic sea floor spreading of the Piemonte-Liguria Ocean, as indicated by U–Pb (in situ ion probe) ages of magmatic zircon between 166 and 160 Ma (Rubatto et al. 1998; Rubatto and Hermann 2003; Beltrando et al. 2010). The magmatic origin is also documented by locally well-preserved pillow structures, e.g., at the Pfulwe locality (Bearth 1967; Barnicoat 1988). Sm–Nd garnet-whole rock dating of metabasaltic rocks from Pfulwe and Lago di Cignana yielded 50 ± 18 Ma (Bowtell et al. 1994) and 40.6 ± 2.6 Ma, respectively (Amato et al. 1999). More precise data were obtained using U–Pb zircon geochronology on rocks from the Lago di Cignana Unit (44.1 ± 0.7 Ma; Rubatto et al. 1998) and the Monviso ophiolite (45.1 ± 1 Ma; Rubatto and Hermann 2003). The zircon data are broadly consistent with Lu–Hf ages of 48.8 ± 2.1 Ma for the LDC Unit (Lapen et al. 2003) and 49.1 ± 1.2 Ma for Monviso (Duchêne et al. 1997). The eclogite-facies ophiolites are overlain by the Combin Zone, which consists of similar rocks derived from the Piemonte-Liguria Ocean but metamorphosed at lower *P–T* conditions (blueschist facies; Reddy et al. 1999). The age of Alpine subduction-related metamorphism in the Combin Zone is not well constrained.

The Sesia-Dent Blanche nappe system, located in the highest structural position, is either assigned to the Austroalpine (Staub 1938) or is treated as Upper Penninic continental crust derived from the Cervinia microcontinent (Trümpy 1992; Froitzheim and Manatschal 1996; Pleuger et al. 2007). The rocks of the Sesia Zone were subducted to eclogite facies conditions during the Late Cretaceous around 79–65 Ma (Duchêne et al. 1997; Rubatto et al. 1999, 2011), and subsequently added to the accretionary prism. Rubatto et al. (2011) distinguished two periods of HP metamorphism, at 79–75 Ma and at 70–65 Ma, separated by a low-pressure stage, based on U–Pb dating of zircon and allanite. By contrast, the Dent Blanche Nappe was affected by only greenschist to blueschist metamorphic conditions (Compagnoni et al. 1977; Dal Piaz 1999; Bousquet et al. 2004). Previously, these basement rocks had partly been affected by a (Late?) Variscan granulite facies overprint, recorded in both the Valpelline series of the Dent-Blanche nappe and in the 2DK (Seconda Zona Dioritico-Kinzigitica) in the Sesia nappe (Fig. 1). In addition to the granulite facies basement of the 2DK series, the Sesia Zone comprises a polymetamorphic basement complex of HP-micaschists, (biotite-bearing) eclogites, glaucophanites, and gabbroic bodies that re-equilibrated under greenschist facies conditions (Compagnoni et al. 1977; Venturini et al. 1996). Continental basement rocks similar to the Sesia Zone are also found at a deeper tectonic level, embedded as tectonic slivers along the contact between the ZSZ and the Combin Zone or within the uppermost part of ZSZ (e.g., Mt. Emilius, Etirol-Levaz; Ballèvre et al. 1986; Dal Piaz 1999), and metamorphosed under eclogite-facies conditions. Rb–Sr phengite ages from these units are 49–40 Ma (Dal Piaz et al. 2001). These results are consistent with SHRIMP U–Pb zircon ages of 47.5 ± 1.0 Ma from Etirol-Levaz (Beltrando et al. 2010).

3 Field relations and sample description

In this study, Lu–Hf isotope data are presented for two eclogite samples (SW9 and SW14) from the TGU. It crops out at the Upper Theodul Glacier, near the location "Trockener Steg" in the southern part of the Zermatt valley (Fig. 2). The TGU appears as a coherent body with a NW–SE extension of 2 km and a thickness of several tens of meters. The TGU is separated from the surrounding ZSZ by well-preserved tectonic contacts, which are nearly parallel to the foliation inside the TGU. Locally, metagabbro forms the base of the TGU (not shown in Fig. 2). The TGU is dissected by several thrust faults, each of them forming the base of an imbricate thrust sheet. Two of these are shown on the map (Fig. 2). Serpentinite is intimately associated with the TGU not only by enveloping it but also by occurring along thrust faults within the TGU. Since serpentinite within the TGU is restricted to these faults, it may be assumed that the TGU formed as a duplex above a layer of serpentinite serving as décollement horizon. The TGU eclogites are interlayered with various types of high-pressure schists: garnet-phengite schists, biotite schists, and metapelitic schists with Ca-poor garnet (Weber 2013). The predominant association of interfingered high-pressure micaschists and eclogites underlain by gabbroic bodies differs significantly from the surrounding ophiolites of the ZSZ. However, they share several lithological similarities with other Sesia-type continental outliers and the polymetamorphic basement sequence of the Sesia zone (Venturini et al. 1996; Weber 2013).

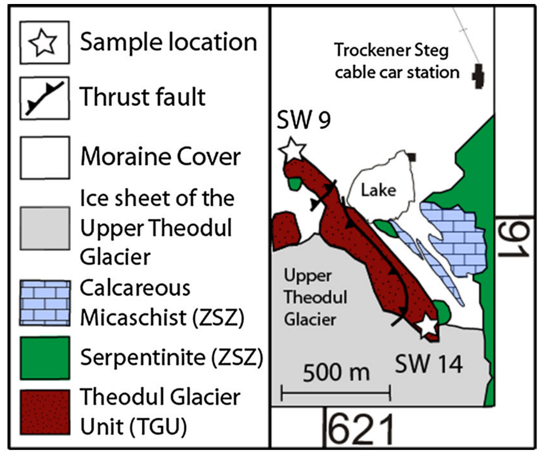

Fig. 2 Simplified geological map of the Trockener Steg area southwest of Zermatt, with the locations of the analysed rock samples marked by white stars. The lithological units of the TGU, which consist of various HP-schists and interbedded eclogite, are shown as a single unit in brown. Note that the TGU is intimately associated with the serpentinites of the ZSZ. Easting and northing on the basis of the Swiss national coordinate system

The samples in this study were taken at a distance of 1.5 km on opposite ends of the TGU and can be clearly distinguished from the adjacent ZSZ rocks in terms of trace element composition and mineral assemblage. Both samples are eclogites with a clearly developed foliation. In hand specimen, garnet, white mica, quartz, and a green mineral of prismatic shape (omphacite or calcic amphibole) are visible. Their high-pressure mineral assemblages comprise garnet + omphacite + glaucophane + phengite + quartz and rutile. During retrogression these minerals were partly replaced by calcic amphibole, epidote, chlorite, paragonite, biotite and feldspar (Fig. 3a). Compared to the common ZSZ eclogites, which are glaucophane-rich metapillow basalts containing also modally abundant paragonite, the TGU eclogites comprise significantly less glaucophane and paragonite but high amounts of phengite and quartz. Relative to the ophiolitic eclogites, the TGU eclogites are enriched in incompatible trace elements such as Y, Zr, Ti, and Nd and in large ion lithophile elements such as Ba and Sr. All chemical characteristics point to a within-plate basalt signature, similar to those found in continental outliers such as the Etirol-Levaz slice (Weber 2013).

Garnet porphyroblasts are crowded with small inclusions, which are mostly rutile needles, fine mica flakes and amphibole. In addition, some garnet crystals are crosscut by oligoclase veins (Fig. 3b). Garnet grains preserve a chemical zoning, which is interpreted as a primary growth feature (see also paragraph 5). At the rims garnet is partially replaced by chlorite and biotite (Fig. 3a). Garnet cores appear unaffected by retrogression. The average

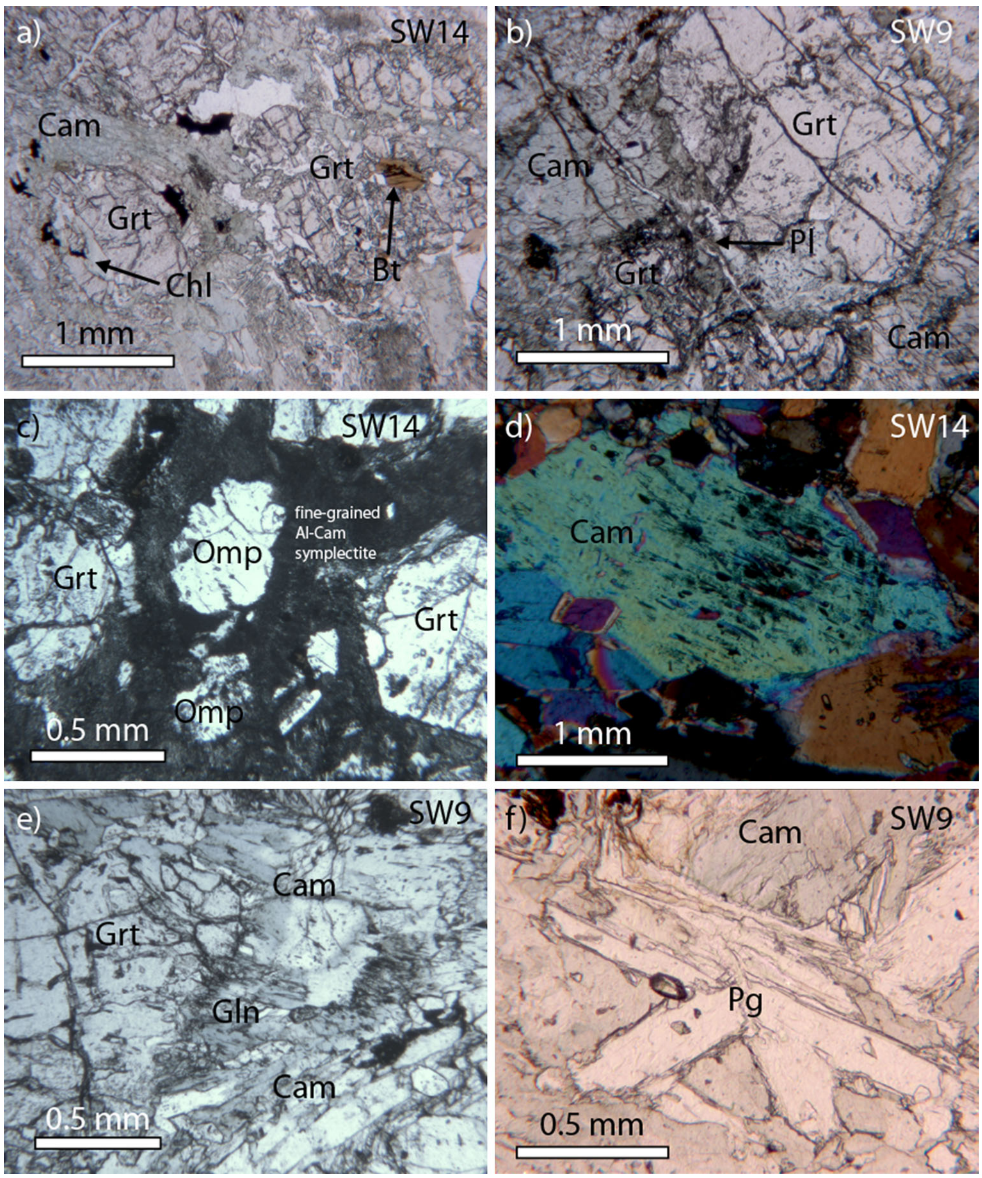

Fig. 3 Photomicrographs of eclogite samples SW9 and SW14. **a**, **b** High-pressure paragenese of garnet and omphacite replaced by chlorite, biotite, calcic amphibole, and plagioclase veins, **c** omphacite replaced by fine-grained amphibole-plagioclase symplectite structures, **d** calcic amphibole pseudomorphically replacing clinopyroxene under crossed polarized light, **e** glaucophane associated with calcic amphibole and **f** randomly orientated paragonite. *Grt* garnet, *Omp* omphacite, *Gln* glaucophane, *Bt* biotite, *Chl* chlorite, *Cam* calcic amphibole, *Pg* paragonite

garnet composition in the TGU eclogites is $Alm_{50-68}Grs_{20-35}Py_{2-15}Sps_{1-15}$ ($n = 100$). Omphacite occurs in some domains and is always surrounded by fine-grained symplectites of albite and calcic amphibole (Fig. 3c). Its average composition has been determined as $Jd_{35-45}DiHed_{45-55}Ac_{5-13}$ ($n = 100$). Omphacite shows an irregular zoning pattern. In some domains, the former presence of magmatic phenocrysts may be indicated by parallel-elongated ore intergrowths within the large amphibole blast (Fig. 3d). From this it can be inferred that magmatic pyroxene is first pseudomorphically replaced by omphacite, which has later been transformed to amphibole. This implies omphacite was present in abundance during the peak metamorphism. White mica is partly aligned to the main foliation, partly randomly oriented. This shows that it formed during and after deformation (Fig. 3e). Two different types of white-mica have been detected in the TGU eclogites, where phengite (3.4 Si p.f.u.) clearly represents a member of the high-pressure paragenesis while paragonite is part of the retrograde mineral assemblage. This is further supported by the observation that phengite is always aligned parallel to the main foliation, while paragonite is present in various textural orientations. Glaucophane occurs in minor amounts associated to abundant calcic amphibole throughout the matrix (Fig. 3f). Analyses of high-pressure amphibole are close to the end-member glaucophane composition and calcic amphiboles show barrositic-edenitic composition. Amphibole does not show significant chemical zoning. In some domains, in particular around garnet, biotite occurs and is therefore thought to be part of the decompression assemblage. It is noteworthy that biotite-bearing eclogites have also been observed in the polymetamorphic basement of the Sesia zone (Venturini et al. 1996). Zircon was only observed in the matrix but not as inclusion in garnet. Zircon dominates the Hf budget of eclogites, which may have important consequences for the geochronological dating. Based on grain morphology both types of zircons, magmatic and metamorphic, occur in both samples.

P–T determinations from calculated assemblage stability diagrams for the eclogites of the TGU yield pressures of 18–22 kbar and temperatures of 500–600 °C using the THERIAK/DOMINO software (de Capitani and Petrakakis 2010; Weber 2013). The following solid solution models have been used: Meyre et al. (1997) for omphacite, Keller et al. (2005) for phengite, and Berman (1988) for garnet. The *P–T* estimates for the TGU eclogites are similar to those of the Mt. Emilius Klippe and the Etirol-Levaz slice, that are 11–13 kbar at 460–480 °C (Dal Piaz et al. 1983) and 16–17 kbar at c. 550 °C, respectively (Kienast 1983; Ballèvre et al. 1986). The derived *P–T* estimates for the continental outliers are in turn consistent with the eclogite metamorphism encountered in the Sesia Zone, where pressure and temperature reached 14–17 kbar and 500–600 °C (Lardeaux and Spalla 1991). In contrast to the typical Zermatt-Saas ophiolites, which were affected by HP and at least locally UHP metamorphic conditions (Reinecke 1991; Bucher et al. 2005; Angiboust et al. 2009), these tectonic elements are clearly outside the stability field of coesite and received only a "relatively high-pressure" imprint (Dal Piaz et al. 2001).

4 Analytical methods

4.1 Sample dissolution and element separation

The collected samples were crushed and divided into two splits. From one split a homogeneous powder was produced, the other was used for garnet separation. For garnet separation, crushed samples were split into grain size fractions by dry sieving. Garnet separates were then handpicked under a stereomicroscope. The separates were cleaned with 2.5 M HCl in an ultrasonic bath and rinsed twice with deionised water. A mixed ^{176}Lu-^{180}Hf and ^{149}Sm-^{150}Nd tracer was added to all samples before digestion. In order to avoid possible effects of inherited isotopic signatures in Hf-bearing phases, the "tabletop" digestion method of Lagos et al. (2007) was applied for digestion of garnet and one set of whole rock powder. This method leaves behind refractory, Hf-bearing phases like rutile and zircon that might preserve unequilibrated isotope signatures. They were digested in Savillex screw-top PFA beakers by addition of $HF–HNO_3–HClO_4$ (4:2:1) and subsequently dried down followed by sample-spike equilibration in 6 N HCl. A second set of whole rock samples was dissolved inside steel-jacketed Teflon PARR-bombs for 5 days at 180 °C. This method ensures complete sample digestion. Lu and Hf were separated from the matrix elements using Eichrom® Ln-Spec resin and the method described by Münker et al. (2001).

4.2 MC-ICPMS measurements

Lutetium and Hafnium measurements were performed on a Thermo Neptune MC-ICPMS at the Steimann-Institut in Bonn. Instrumental mass bias on measured Hf isotope ratios were corrected by using the exponential law and a $^{179}Hf/^{177}Hf$ of 0.7325. Measured $^{176}Hf/^{177}Hf$ ratios presented in this work are reported relative to a $^{176}Hf/^{177}Hf$ ratio of 0.282160 for the Münster Ames Hf standard that is isotopically identical to the JMC-475 standard. Naturally occurring Yb in the Lu cuts was used for mass bias correction on Lu isotope ratios (Vervoort et al. 2004). Correction of the ^{176}Yb interference on ^{176}Lu was achieved by using the trend of ln ($^{176}Yb/^{171}Yb$) vs. ln ($^{174}Yb/^{171}Yb$)

from Yb-only standard analyses before the Lu measurements (e.g., Vervoort et al. 2004; Lagos et al. 2007). Procedural blanks were <24 pg for Lu and <72 pg for Hf and were always insignificant. Hafnium compositions were calculated using both the tracers and the natural Lu compositions (Amelin et al., 2011). The difference between the two was then added to the external reproducibilities that were estimated by an empirical relationship 2σ external reproducibility $\approx 4\sigma_m$ (σ_m = standard error of a single analysis; e.g., Bizzarro et al. 2003). Regressions of isochrons and ages were calculated using ISOPLOT v. 2.49 (Ludwig 2001) and a decay constant of λ $^{176}Lu = 1.867 \times 10^{-11}$ year^{-1} (Scherer et al. 2001; Söderlund et al. 2004).

4.3 Electron microprobe analysis

Electron microprobe analyses were carried out on a JEOL Superprobe JXA 8200 at the Steinmann-Institut, Bonn, using a beam current of 15 nA and an acceleration voltage of 15 kV. Elemental maps of Fe, Mg, Ca, and Mn were used to characterise the 2D distribution of major elements in single garnet grains. The dwell time of spot analyses during map scans was set to 100 ms.

4.4 Laser ablation analysis

Laser ablation analyses were carried out at the Steinmann-Institut in Bonn using a Resonetics M50-E ATL Excimer 193 nm laser system coupled to a Thermo-Finnigan X-series 2 quadrupole ICPMS, following the routine described in Kirchenbaur et al. (2012). Spot sizes were set between 55 and 75 µm depending on grain size and the amount of visible inclusions. Laser fluence at the sample surface was measured at 7 J/cm^{-2}. The laser repetition rate was set to 10 Hz. Count rates were normalized using ^{29}Si as the internal standard and NIST-612 standard reference material as external standard. The isotopes ^{29}Si, ^{43}Ca, ^{55}Mn, ^{89}Y, ^{175}Lu, and Hf were monitored. The oxide production rates were kept below 0.5 % in order to avoid the possibility of any significant oxide molecular interference on the REE isotopes that were monitored (measured ThO/Th ratios <0.5 %; Kent and Ungerer 2005). Data reduction and evaluation followed the procedure of Longerich et al. (1996).

5 Results

Major-element maps of single garnet grains of the two eclogite samples are presented in Fig. 4. Garnet grains are mostly euhedral and show a bell-shaped distribution of Mn, Ca and Fe/(Fe+Mg) with high contents of Mn and Ca in the cores and decreasing contents towards the rims. Such a distribution is regarded as a preserved prograde growth-zoning pattern (Konrad-Schmolke et al. 2005; Skora et al. 2009). Lutetium concentration profiles of single garnet grains obtained by laser ablation analyses are presented in Fig. 5. Both samples retained the initial pattern of garnet growth with high Lu-concentrations in the core that decrease towards the rims (Skora et al. 2006). This implies that Alpine peak metamorphism did not lead to isotopic re-equilibration of the Lu–Hf system.

Concentrations of Lu and Hf and ratios of $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ are presented in Table 1. An isochron that is based on three garnet separates and the completely digested whole rock of sample SW9 yields an age of 56.5 ± 2.7 Ma (MSWD 0.47, $n = 4$, Fig. 6). It is identical with an isochron age that is based on garnet and that whole rock sample that was digested by the selective "tabletop" procedure (56.4 ± 2.8 Ma; MSWD 0.47, $n = 4$). Completely digested whole rock and three garnet separates of sample SW14 yield an isochron age of 58.2 ± 1.4 Ma (MSWD 1.8, $n = 4$, Fig. 7). This age is also identical with an isochron age that is based on garnet and selectively digested whole rock (57.9 ± 1.5 Ma; MSWD 1.7, $n = 4$). Hence, the effects of inherited isotope signatures in phases like zircon are negligible in these samples. Also, Lu–Hf garnet-whole rock ages of both samples are identical within error.

6 Discussion

6.1 Geological significance of the Lu–Hf results

For the interpretation of Lu–Hf ages it is of fundamental interest if the observed chemical zoning of garnet represents an undisturbed prograde growth pattern (Hollister 1966). The crossing of the closure temperature (Dodson 1973) may reset the Lu–Hf isotope system within garnet, and the ages defined by the isochrons may then reflect cooling instead of prograde crystallisation. To show that the investigated samples preserve an age linked to the prograde path, a useful proxy is the zoning in the content of major elements, Mn^{2+}, Lu^{3+}, and Y^{3+} (Figs. 4, 5), which suggest that Lu–Hf ages represent crystallization rather than cooling ages. This is in agreement with all reported estimates for the closing temperature of the Lu/Hf isotope system (700 °C: Ganguly and Tirone 1999; Scherer et al. 2000; 720–755 °C: Skora et al. 2006; 850 °C: Schmidt et al. 2011; 1000 °C: Shu et al. 2012), since the eclogite samples from the TGU were affected by maximum temperatures of less than 700 °C. The shape of the Lu^{3+} and Y^{3+} patterns presented here are similar to those reported by Skora et al. (2006) for

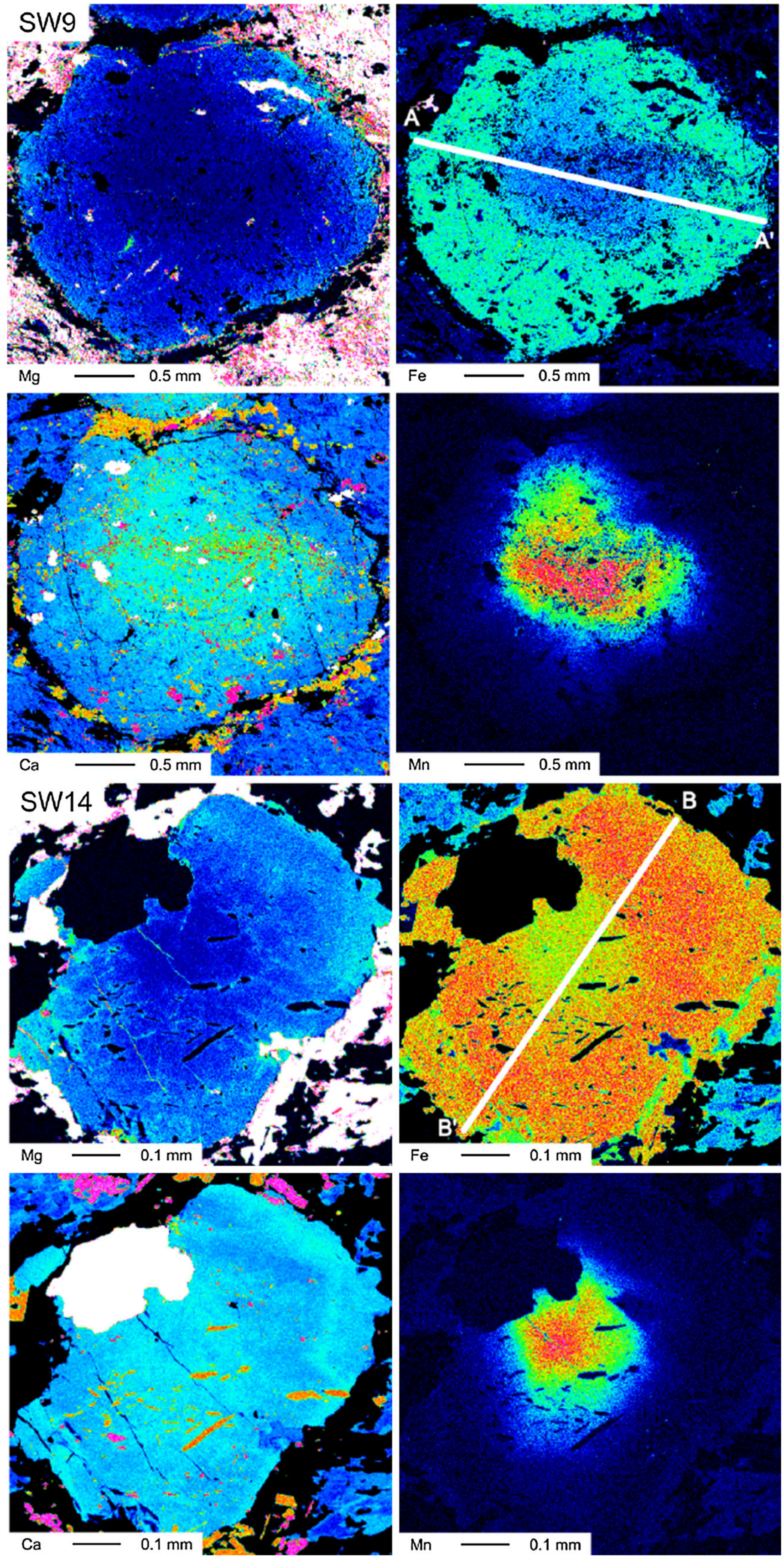

Fig. 4 Major element distribution maps of garnets from samples SW9 and SW14. Traces *AA′* and *BB′* correspond to analyses given in Fig. 5. Note the enrichment of Mn in the cores

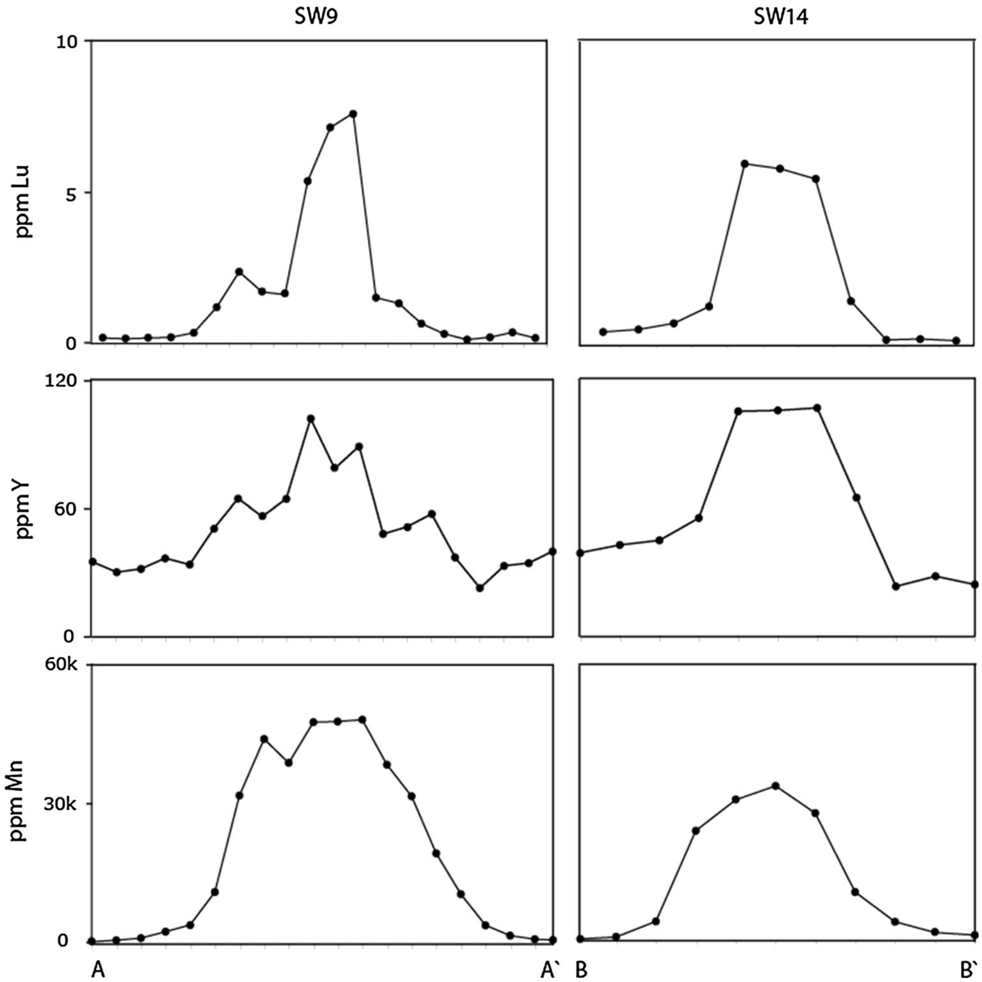

Fig. 5 Lutetium, Y and Mn garnet zoning profiles for SW9 and SW14

Table 1 Lu and Hf element and isotope data of the whole rocks and garnet separates for Theodul Glacier Unit eclogite samples

Sample	ppm Lu	ppm Hf	$^{176}Lu/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf$	2σ
SW9						
WR(cd)	0.319	5.90	0.007664	15	0.282798	34
WR(sd)	0.308	0.295	0.1481	3	0.282951	26
Grt1	1.76	0.135	1.852	4	0.284729	103
Grt2	1.57	0.123	1.812	4	0.284954	570
Grt3	1.41	0.103	1.952	4	0.284874	186
SW14						
WR(cd)	0.382	9.59	0.005656	11	0.282721	13
WR(sd)	0.357	0.216	0.2353	4	0.282988	29
Grt1	1.32	0.0581	3.237	6	0.286516	335
Grt2	1.38	0.0494	3.969	8	0.286998	107
Grt3	1.40	0.0548	3.627	7	0.286781	430

Uncertainties on both $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ ratios are the estimated 2σ external reproducibilities, as described in the text

WR(*cd*) whole rock complete digestion, *WR*(*sd*) whole rock selective digestion

where the authors also propose that garnet REE patterns within the ZSZ eclogites have not been reset. As a consequence, the isochron ages of 56.5 ± 2.7 and 58.2 ± 1.4 Ma can confidently be interpreted as prograde crystallization ages. Since the TGU was part of the Penninic subduction zone system, they can therefore be

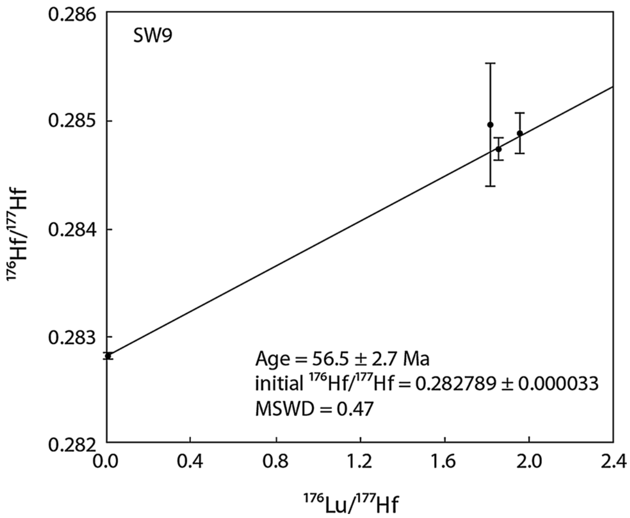

Fig. 6 Lu–Hf garnet-whole rock isochron plot for sample SW9 from the Trockener Steg area. See Table 1 for data used to calculate the isochron

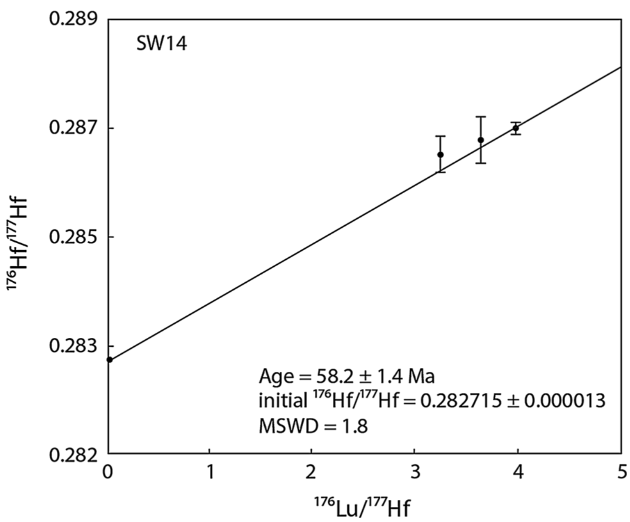

Fig. 7 Lu–Hf garnet-whole rock isochron plot for sample SW14 from the Trockener Steg area. See Table 1 for data used to calculate the isochron

directly related to a subduction zone setting. Hence, at around 58–56 Ma, the rocks of the TGU were buried to depths of 30–35 km on their way down the subduction zone, assuming the geochronological data refer to the early stages of garnet growth (Fig. 9c).

6.2 The Zermatt-Saas zone: one terrane or a composite of slices?

Based on the lithological composition, the TGU is interpreted as a continental sliver comparable to Etirol-Levaz, Glacier-Rafray, Mt. Emilius, and other "Austroalpine" slivers in the Zermatt-Saas Zone. Using Rb–Sr geochronology on phengite, Dal Piaz et al. (2001) dated eclogite-facies metamorphism in some of the continental slivers—but not in the TGU—at 49–40 Ma, and in the Zermatt-Saas Zone ophiolites at 46–43 Ma. From the similarity of these age ranges they concluded that the "Austroalpine" slivers were derived from one or more intraoceanic extensional allochthon(s) that were already emplaced in the Piemonte-Liguria Ocean by pre-oceanic rifting, and then subducted together with the ophiolites. In this view, the Zermatt-Saas zone represents a coherent terrane that was subducted and exhumed in one piece. This model was supported by the finding of Jurassic zircon domains in the Etirol-Levaz sliver which were interpreted as results of melt infiltration associated with the intrusion of gabbro in the underlying ophiolite (Beltrando et al. 2010). Lu–Hf ages, however, which record incipient garnet growth during subduction, show a time difference of c. 8–10 Ma between the TGU (58–56 Ma) and the Zermatt-Saas Zone at Lago di Cignana (c. 48 Ma). As the older age is found more to the North (TGU) and the younger age to the South (Lago di Cignana), and the subduction zone which consumed the Piemonte-Liguria Ocean probably dipped southeast (e.g., Dal Piaz et al. 2001), the age difference is opposite to what would be expected if the two units were parts of one coherent terrane. Consequently, although the time of exhumation of the TGU is unknown, our data rather support the view that the Zermatt-Saas Zone is a composite of units with different tectonic histories (e.g., Negro et al. 2013). However, the arrangement of these units is probably not coincidental but follows the trend of decreasing metamorphic age from structurally higher to deeper tectonic units which is a general rule for high-pressure rocks in the Alps (Bearth 1967; Berger and Bousquet 2008), reflecting progressive accretion to the orogenic wedge: The TGU is found at the structural top of the Zermatt-Saas Zone and yielded the highest age known from this zone. More data from other parts of the ZSZ are needed to confirm this trend and to define the different tectonometamorphic units.

6.3 Palaeogeographic position of the TGU

The timing of eclogite-facies metamorphism in the TGU is intermediate between the Sesia nappe and the Zermatt-Saas ophiolites. As subduction generally prograded towards northwest (Laubscher 1988, 1991; Escher et al. 1997; Rosenbaum and Lister 2005) and the character of the TGU rocks is continental rather than oceanic (Weber 2013), we assume that the TGU originally belonged to the north-western continental margin of the Cervinia microcontinent or was at least located close to it (Fig. 9). The reconstruction in Fig. 9 is unconventional in that the paleogeographic origin of the Tsaté nappe is located between Cervinia and Adria, following Pleuger et al. (2007). Pleuger et al. (2007) explain the present position of the Tsaté nappe below the Sesia nappe with out-of-sequence thrusting of the Sesia nappe between 44 and 35 Ma. This process led to duplication of the Sesia-derived units. The continental slices at the ZSZ-Tsaté boundary were inserted within a lower structural position, and the Sesia and Dent Blanche nappes represent the upper structural elements.

6.4 Implications for the "Paleocene restoration"

Our new data partly fill the Paleocene time gap in the geochronological record of high-pressure metamorphism in the Central and Western Alps. So far, no evidence existed for eclogite-facies metamorphism between c. 65 Ma (Sesia Nappe) and c. 49–48 Ma (Lago di Cignana and Monviso) (Fig. 8). The Lu–Hf ages from the TGU, c. 58–56 Ma, fall into the middle of this time span, making it very likely that subduction continued from the Late Cretaceous into the Eocene.

On the other hand, as derived from the magnetic anomaly pattern in the Atlantic, Europe–Africa convergence almost came to a stillstand between 65 and 51 Ma (Trümpy 1973; Frisch 1979; Rosenbaum and Lister 2005; Schettino and Turco 2011). Therefore, subduction was probably balanced by extension of the upper plate, as is usually the case during roll-back of a subduction zone. Such roll-back extension during the Paleogene was already suggested by Rosenbaum and Lister (2005). Roll-back extension was, however, not restricted to the Paleocene but lasted from c. 80 to 67 Ma in the Austroalpine (Froitzheim et al. 1997, 2012) and from 55 to 45 Ma in the Sesia Zone (Babist et al. 2006). This reflects a northwestward migration of the extensional process, in the wake of the equally northwestward-migrating subduction-related shortening.

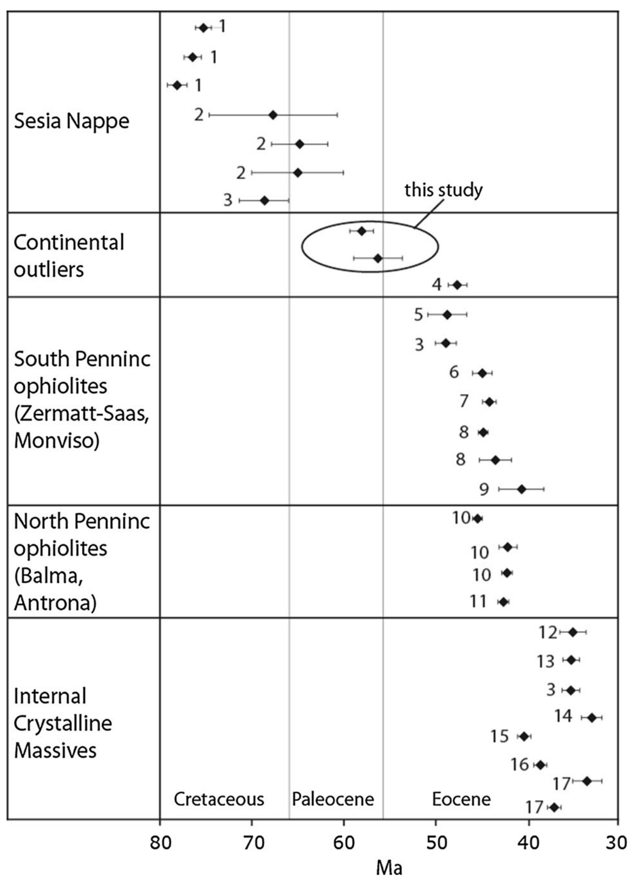

Fig. 8 Ages of HP and UHP metamorphism in the western Alps from Lu–Hf and Sm–Nd garnet, U–Pb SHRIMP zircon, U–Pb SHRIMP allanite, U–Pb rutile, and Rb/Sr phengite inclusions in garnet dating. *1* Rubatto et al. (2011), *2* Rubatto et al. (1999), *3* Duchêne et al. (1997), *4* Beltrando et al. (2010), *5* Lapen et al. (2003), *6* Rubatto and Hermann (2003), *7* Rubatto et al. (1998), *8* de Meyer et al. 2014, *9* Amato et al. 1999, *10* Herwartz et al. (2008), *11* Liati et al. (2005), *12* Liati and Froitzheim (2006), *13* Lapen et al. (2007), *14* Rubatto and Gebauer (1999), *15* Rubatto et al. (2001), *16* Gebauer et al. (1997) and *17* Radulescu et al. (2009). Ages from this study, 56.5 ± 2.7 and 58.2 ± 1.4 Ma, are indicated by *ellipse*

6.5 Reconstruction of the tectonic evolution

Figure 9 attempts a reconstruction of the tectonic evolution of the western Swiss-Italian Alps, based on the existing age data and structural retrodeformation. The complicated paleogeography with continental ribbons and intervening ocean basins strongly influenced the orogenic evolution (e.g., Rosenbaum and Lister 2005) and favoured the exhumation of HP and UHP units (Husson et al. 2009). Altogether, tectonic shortening prograded from southeast to northwest. We assume that microcontinent collisions led to the formation of new, short-lived subduction zones in more external positions (Royden and Husson 2006, 2009). The collision of the Cervinia microcontinent at c. 70–65 Ma caused a new subduction zone to form in the northern sub-basin of the Piemonte-Liguria Ocean (Fig. 9c). Likewise, the Brianconnais collision at c. 50 Ma started subduction in the North-Penninic (Valaisan) basin (Fig. 9d; Herwartz et al. 2008). Between collisions, subduction of oceanic crust went on without major accretion and rollback occurred. The European continental margin started to be subducted at c. 40 Ma, which brought the Alps into a state of pure collisional orogeny (Fig. 9e).

7 Conclusions

1. For the eclogites of the TGU, two Lu–Hf ages of 56.5 ± 2.7 and 58.2 ± 1.4 Ma were obtained. Combined with garnet element profiles, it can be shown that these ages date a stage close to the prograde growth of

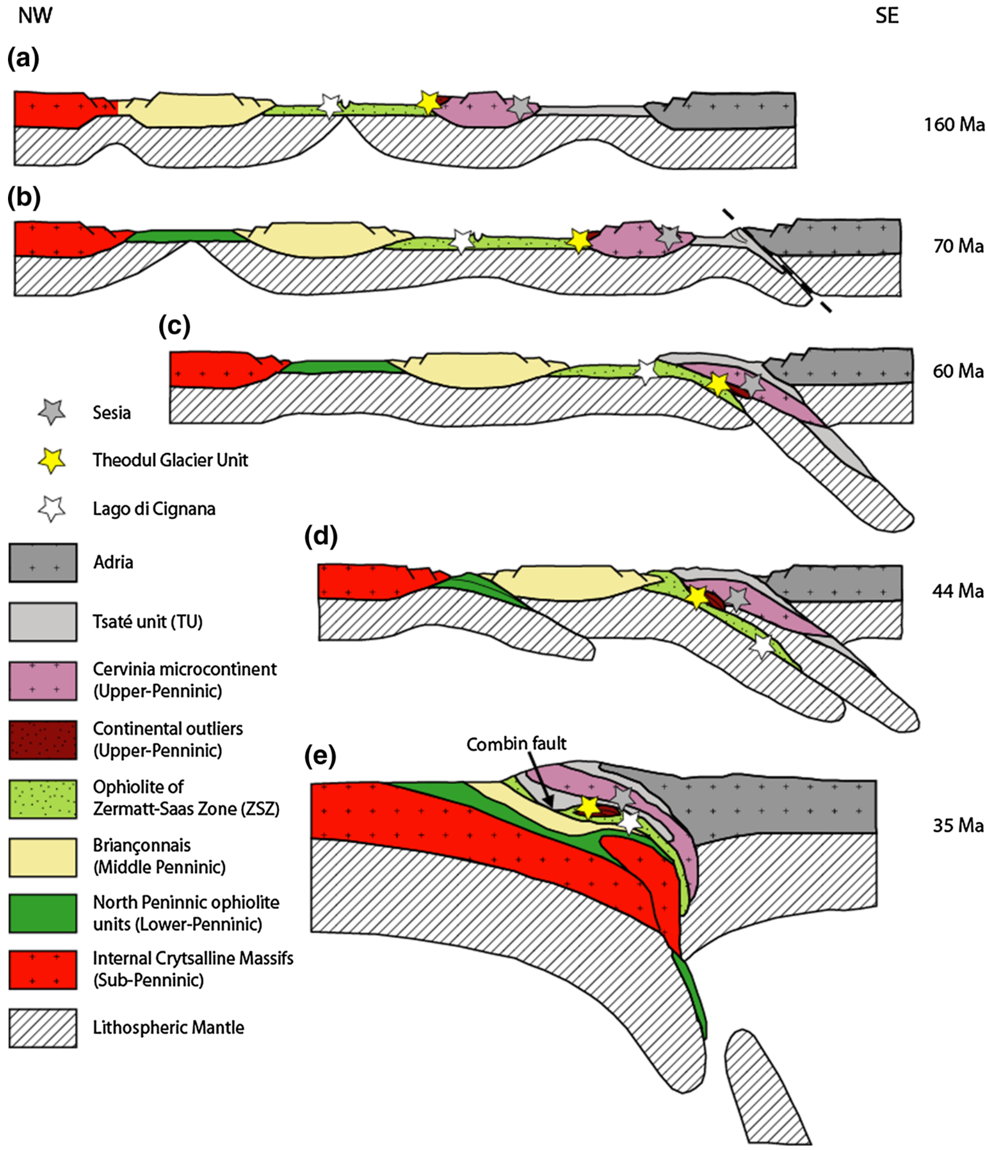

Fig. 9 Schematic sketch, showing simplified evolution of the Western Alps in the time interval from 160 to 35 Ma. Two Ocean basins existed, the Valais and the Piemonte-Liguria Ocean. **a** After the opening of the Piemonte-Liguria Ocean, the TGU (*yellow star*) was part of the passive margin of the Cervinia microcontinent. **b** The Briançonnais terrane was separated from the European continent by rifting of the Valais Ocean in the Late Jurassic–Early Cretaceous. Subduction startet around 70 Ma at the latest. **c** TGU was subducted and accreted while other units of the Zermatt Saas Zone were still near the surface. **d** Subduction propagated continuously to the NW, while the Lago di Cignana Unit (*white stars*) was subducted to UHP depth. The process lasted until the arrival of the Briançonnais microcontinent which blocked the subduction zone and the subduction of the Valais Ocean started. **e** Between 44 and 35 Ma, the western Alpine nappe stack was formed and the exhumation of the ZSZ and associated "Austroalpine outliers" took place. Exhumation was accompanied by thrusting along the Combin fault. In this model, the Internal Crystalline Massives are located at the European margin (Gebauer 1999; Froitzheim 2001). *Sketches* are not to scale

garnet. The ages can be related to a subduction-driven burial path, which implies that the TGU passed through a depth of approximately 30–35 km in the late Paleocene. Since subduction within the western Alps migrated in time from internal to external units, the TGU is proposed to represent a fragment of the distal margin of the Cervinia microcontinent.

2. The new Lu–Hf ages fall into the Paleocene restoration phase which separates two main orogenic events ("Eo-Alpine" and "Meso-Alpine"). Our results indicate that subduction continued throughout this period.
3. Subduction during the Paleogene occurred in a time of very low convergence rates between Europe and Africa. This situation may be attributed to northwest-

directed rollback, kinematically linked to extension in the upper plate.

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