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Size and exhumation rate of ultrahigh-pressure terranes linked to orogenic stage

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ABSTRACT

A growing set of data indicates a stark contrast between the evolution of two types of ultrahigh-pressure (UHP) terranes: large terranes that evolved slowly (over 10–30 Myr), and small terranes that formed and were exhumed on timescales of <10 Myr. Here we compare the characteristics – area, thickness, formation rate, exhumation rate, age, and tectonic setting – of these two endmember types of UHP terrane worldwide. We suggest that the two UHP terrane types may form during different orogenic stages because of variations in the buoyancy and traction forces due to different proportions of subducting crust and mantle lithosphere or to different rates of subduction. The initial stages of continent collision involve the subduction of thin continental crust or microcontinents, and thus tectonic forces are dominated by the density of the oceanic slab; subduction rates are rapid and subduction angles are initially steep. However, as collision matures, thicker and larger pieces of continental material are subducted, and the positive buoyancy of the down-going slab becomes more prominent; subduction angles become gentle and convergence slows. Assessing the validity of this hypothesis is critical to understanding the physical and chemical evolution of Earth's crust and mantle.

1. Introduction

Regionally extensive exposures of coesite- and/or diamond-bearing rocks are referred to as ultrahigh-pressure (UHP) terranes. Since the discovery of coesite in metamorphic rock more than 25 years ago (Chopin, 1984; Smith, 1984) revolutionized our understanding of plate tectonics, the number of recognized UHP terranes has increased to more than 20 (Liou et al., 2004; Rumble et al., 2003). With this recognition, our understanding of how subduction and exhumation of continental material influence the growth and decay of mountain belts, the modification of continental crust, the geochemical evolution of the mantle, and the forces acting on tectonic plates has dramatically increased. Although UHP terranes are postulated to form in a range of tectonic settings, including subduction erosion (Stoeckhert and Gerya, 2005), intracontinental shortening (Pysklywec et al., 2000), and lithospheric rifting (Little et al., 2011), most are presumed to represent once-subducted microcontinents or continental margins (Liou et al., 2004).

With few exceptions, data on the age, size, thickness, and residence time (here chosen as the period of time at greater than mid-crustal depths) define two endmember types of UHP terrane: i) Small, young, thin and fast (rapidly subducted and exhumed) terranes, and ii) large, old, thick and slow terranes (Table 1). The oldest exposed UHP terranes are 620 Ma (Jahn et al., 2001), and active orogens contain UHP terranes as young as 8 Ma (Baldwin et al., 2004). The areal extent of UHP terranes – here taken to be the area of UHP and contiguous HP eclogite-facies rocks (or amphibolite-facies rocks hosting eclogite) – ranges from >20,000 km^2 to <50 km^2. UHP terranes were originally all assumed to be thin (<10 km; Ernst, 2006); however, a number of thick (≥10 km) UHP terranes have been recognized (Hacker et al., 2000; Root et al., 2005).

Geochronologic data indicate rapid (<5 Myr) exhumation of most UHP terranes (Hacker et al., 2003; Parrish et al., 2006; Root et al., 2005; Rubatto and Hermann, 2001; Zheng et al., 2003), but a few UHP terranes were exhumed long after reaching peak depths (Gilotti et al., 2004; Hacker et al., 2000; Kylander-Clark et al., 2008). Subduction rates and residence times are less well constrained, but some were demonstrably short (<15 Ma; Amato et al., 1999; Lapen et al., 2003; Parrish et al., 2006)—and some demonstrably long (>20 Ma; Hacker et al., 2006; Kylander-Clark et al., 2007, 2009; Mattinson et al., 2006; McClelland et al., 2006).

This paper categorizes the better-known UHP terranes into these two main types, and suggests possible orogenic processes and tectonic environments that may have produced this duality.

2. Small vs. big UHP terranes

UHP terranes with well-studied P–T–t paths, such as the Dabie–Sulu terrane of eastern China, the Western Gneiss region (WGR) of Norway—both of which are large terranes – and the Dora Maira massif of the western Alps—a small terrane – are used to characterize

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Table 1
Characteristics of well-studied ultrahigh-pressure terranes.

Terrane	*Minimum volume*[a]		Peak UHP age (Ma)[c]	Lower-crustal age (Ma)[d]	Mid–upper crustal age (Ma)[e]	Subduction duration (Myr)[f]	Exhumation duration (Myr)	Total duration (Myr)[g]
	Area[b] (km^2)	Thickness (km)						
Lago Cignana[1]	<500 (2)	0.3	40.6 ± 2.6	n/d	38 ± 2	~8	~2	~10
Kaghan Valley[2]	<1000	<5	46.4 ± 0.1	n/d	44.1 ± 1.0	7–9	~2	9–11
Papua New Guinea[3]	4000	n/d	7.9 ± 1.9	~3.5	~1.5	n/d	~4	>4
Tso Morari[4]	5000	<15	53.3 ± 0.7	47 ± 11	48 ± 2	n/d	~5	>5
Dora Maira[5]	500 (50)	1	35.4 ± 2.7	32.9 ± 0.9	31.8 ± 0.5	n/d	~4	>4
Erzgebirge[6]	2500 (1)	3	336.8 ± 2.8	330.2 ± 5.8	340–330	n/d	<7	n/d
Kokchetav[7]	<1500	<2	~533	528 ± 8	~529	n/d	~6	>6
Greenland[8]	40,000 (>40)	>5	364 ± 8	342 ± 6	~329	n/d	~35	>35
Qaidam[9]	25,000	n/d	446–423	n/d	401.5 ± 1.6	>13	>21	~58
Western Gneiss Region[10]	30,000 (5,000)	>15	405–400	~390	385–375	>20	>15	>35
Dabie–Sulu[11]	30,000 (10,000)	>10	245–222	222–210	200–180	>12	>20	~45

For justification of reported ages, see discussion at end of Table A.1
1) Amato et al., 1999; Lapen et al., 2003; 2) Kaneko et al., 2003; Parrish et al., 2006; 3) Monteleone et al., 2007 ; 4)de Sigoyer et al., 2000; Leech et al., 2007; 5) Gebauer et al., 1997; Henry et al., 1993; Rubatto and Hermann, 2001; 6) Kröner and Willner, 1998; Massonne et al., 2007; Werner and Lippolt, 2000; 7) Hacker et al., 2003; Hermann et al., 2001; Kaneko et al., 2000; Shatsky et al., 1999; Yamamoto et al., 2000 ;8) Gilotti and Krogh Ravna, 2002; Gilotti et al., 2004; McClelland et al., 2006; 9) Mattinson et al., 2006; Song et al., 2006; 10) Kylander-Clark et al., 2007, 2008, 2009; Root et al., 2005; 11) Hacker et al., 2000, 2006. For a complete list of data, references and explanations for the dataset presented in this table, see Table A.1.

[a] Because not all terranes are horizontal and well exposed, *area x thickness* provides a minimum volume estimate.
[b] Area containing eclogite-facies (i.e., HP) outcrops (area within HP unit that contains confirmed UHP outcrops in parentheses).
[c] U–Pb zircon, Lu–Hf garnet, or Sm–Nd garnet ages of eclogites that contain evidence of UHP conditions (e.g., inclusions of coesite).
[d] U–Pb zircon or titanite or Sm–Nd garnet ages interpreted to represent amphibolite-facies metamorphism.
[e] Reflects mid-crustal cooling through ~400 °C (e.g., ^{40}Ar/^{39}Ar muscovite, U–Pb rutile).
[f] Difference between the oldest HP ages interpreted as prograde and the oldest ages interpreted as UHP.
[g] Difference between the earliest HP age and the mid-crustal age.

the two types of endmembers. A summary of these terranes is given in Table 1 and Fig. 1, and a detailed discussion of the >150 studies represented herein is in Supplementary Table A.1. Eclogite-facies rocks in the Dabie–Sulu terrane cover ~30,000 km^2—of which 10,000 km^2 are UHP (Hacker et al., 2006); geologic maps, cross sections, and seismic profiles suggest that the (U)HP unit is at least 10 km thick (Hacker et al., 2000; Wang et al., 2000). The terrane reached eclogite-facies conditions by ~245 Ma and was exhumed to mid-crustal levels by ~220–200 Ma (U–Pb, Lu–Hf, Sm–Nd ages, and ^{40}Ar/^{39}Ar ages; Hacker et al., 2009; Zhang et al., 2009); HP conditions lasted for more than 25 Myr. The WGR, exposing ~30,000 km^2 of eclogite-facies rocks (UHP rocks underlie ~5,000 km^2; Root et al., 2005), spent more than 25 Myr at HP conditions: subduction began prior to ~425 Ma (Lu–Hf garnet ages; Kylander-Clark et al., 2007), and the UHP terrane was exhumed to mid-crustal levels by 400–380 Ma (^{40}Ar/^{39}Ar muscovite ages; Root et al., 2005). The lengthy isothermal decompression, particularly of the UHP rocks, implies that the WGR was >15 km thick (Kylander-Clark et al., 2009). The Dabie–Sulu and Western Gneiss region UHP terranes thus exhibit similar characteristics: both are exposed in inactive orogens, spent a relatively long time at high pressure (>20 Myr), are exposed over large areas (>20,000 km^2), and are thick (≥10 km). In contrast, the UHP terrane in the Dora Maira massif spent only 3.3 ± 1.3 Myr at depth (U–Pb zircon and titanite; Gebauer et al., 1997; Rubatto and Hermann, 2001), is thin (~1 km), and UHP rocks represent only ~50 km^2 of a <500 km^2 eclogite-facies unit (Henry et al., 1993) in an *active* orogen.

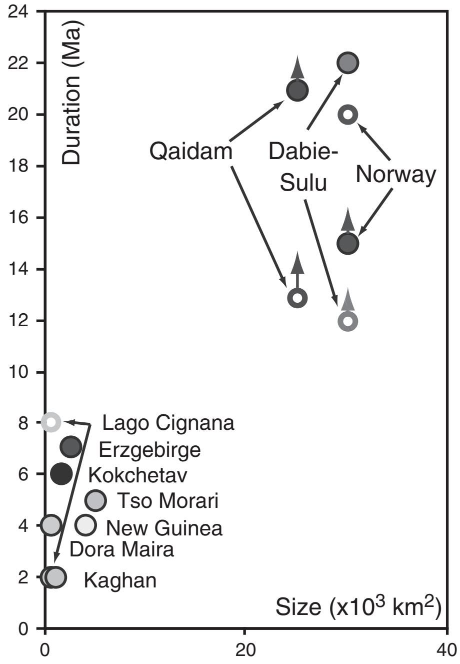

Fig. 1. UHP terrane size versus formation duration.Well-studied UHP terranes define two separate groups: those that are large and spent a long time at depth, and those that are small and spent a relatively short period at depth. Symbol shading indicates terrane age (darkest are oldest). Where data are available, the time spent for terrane burial is shown with open symbols and the time spent for terrane exhumation to mid-crustal levels is shown with filled symbols (See Table 1). 'Size' refers to the area of exposed eclogite-facies rocks, which includes HP and UHP rocks.

Other less-studied UHP terranes exhibit characteristics similar to these better-known endmembers (Table 1, Fig. 1, Table A.1). For example, the North-East Greenland Eclogite Province (NEGEP; >15 km thick) and the Qaidam UHP terrane (unconstrained thickness) are large (>25,000 km^2) and spent a long time at depth (>20 Myr). Conversely, the Papua New Guinea, Lago Cignana, Tso Morari, and Kaghan Valley (U)HP localities underlie small areas (<5000 km^2), were subducted and exhumed over short periods (<10 Myr), are <3 km thick, and crop out in active orogens. There may be some UHP terranes that cannot be neatly shoe-horned into either of these endmembers: the Erzgebirge unit in the Bohemian Massif and the poorly exposed Kokchetav UHP terrane are old (~340 Ma and ~535 Ma, respectively), but current data indicate that their size, thickness, and exhumation rate are similar to small UHP terranes (Table 1). These terranes are discussed further below. Not discussed are numerous other UHP terranes – such as those in Rhodope, Greece, Central Europe (parts of the Variscan orogen other than the Erzgebirge), and Brazil and Mali (the Pan-African orogen) – whose tectono-chronologic framework is less well constrained because