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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

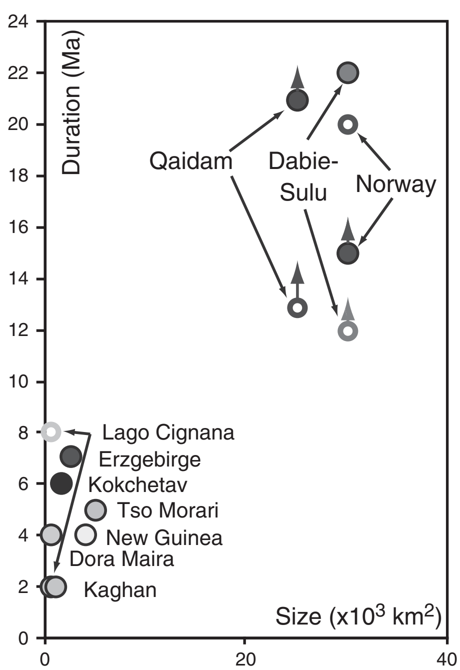

Fig. 1. UHP terrane size versus formation duration.Well-studied UHP terranes define two separate groups: those that are large and spent a long time at depth, and those that are small and spent a relatively short period at depth. Symbol shading indicates terrane age (darkest are oldest). Where data are 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.

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.

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 of poor exposure, a dearth of data, and/or post-(U)HP overprinting events.

In summary, most UHP terranes can be categorized into one of two groups: i) small, thin, young, and fast (rapidly subducted *and* exhumed), and ii) large, thick, old, and slow (slowly subducted *and* exhumed). Recognizing this duality (Kylander-Clark et al., 2009) has been a significant step forward, but the cause of the duality remains unclear.

3. Early vs. mature orogenic stage model

Did fundamentally different geodynamic/tectonic process(es) produce this bimodal set of UHP terranes? Although differences in metamorphic PT gradients (Brown, 2008), igneous rock abundances (e.g., TTG–anorthosite–Rapakivi suites), ophiolite outcrops, and accretionary-wedge outcrops (Hamilton, 2011) imply that plate tectonics may be an exclusively late Proterozoic–Phanerozoic phenomenon, it is unlikely that major changes in plate tectonics since the latest Proterozoic (the earliest recognized UHP rocks; Jahn et al., 2001) are responsible for producing these two types of UHP terrane. Secular cooling would have meant warmer early subduction, leading to slower, hotter subduction of smaller continental slivers (Pollack, 1997; Sleep, 2000); and colder late subduction, leading to faster, colder subduction of larger continental slivers. This expectation is inconsistent with the observations (Fig. 1).

As an alternative, we hypothesize that small, thin, young, and fast UHP terranes formed early during orogeny, and large, thick, old, and slow UHP terranes formed during the end of orogeny. This hypothesis fits the observations for both groups of terranes, allows for the exception noted above, and has significant impact on our understanding of the effects that UHP tectonism has on a variety of geologic processes. Our rationale is as follows: the transition from oceanic to continental subduction results in reduced subduction angle and slower vertical subduction velocity. The buoyant crustal material and the thicker, stronger continental lithosphere are entrained in the subduction zone and counteract the negative buoyancy of the dense oceanic lithosphere (Billen and Hirth, 2007; Sobouti and Arkani-Hamed, 2002). As the volume of the subducted continent increases, the subduction angle and plate velocity continue to decrease. This reduction in subduction angle and plate velocity provides a mechanism to explain the two types of UHP terrane (Fig. 2). During the *early* stages of continent collision – characterized by subduction of a microcontinent or thinned continental margin – subduction forces are dominated by oceanic lithosphere and subduction is likely fast and steep; UHP terranes formed in such settings are small and subducted and exhumed quickly. During the *mature* stages of continent collision – characterized by subduction of normal continental lithosphere – subduction is slower and the subduction angle gentler; such settings produce large UHP terranes that form over longer periods of time.

Because exhumation rate has commonly been tied to the positive buoyancy of subducted terranes (Ernst and Liou, 2008), one might expect that large terranes should exhume more rapidly than small ones. The opposite appears to be true, however (Fig. 1), and one or more factors may be responsible. If large and thick terranes remain attached to thick (typical continental) lithosphere, they may be less buoyant than small and thin terranes attached to the thinned lithosphere typical of continental margins. In addition, during mature stages of orogenesis, continent collision produces overthickened crust, which may arrest the rise of a UHP terrane at Moho depths (lower-crustal age in Table 1), prolonging the exhumation period (Walsh and Hacker, 2004). This 'Moho arrest' is indicated for many UHP terranes, which appear to have a two-stage exhumation history in which an initial fast exhumation to ~1 GPa is followed by slower exhumation to the surface (Rubatto and Hermann, 2001). Large UHP terranes may also spend more time at peak depths because their greater thickness requires a longer period of heating to weaken

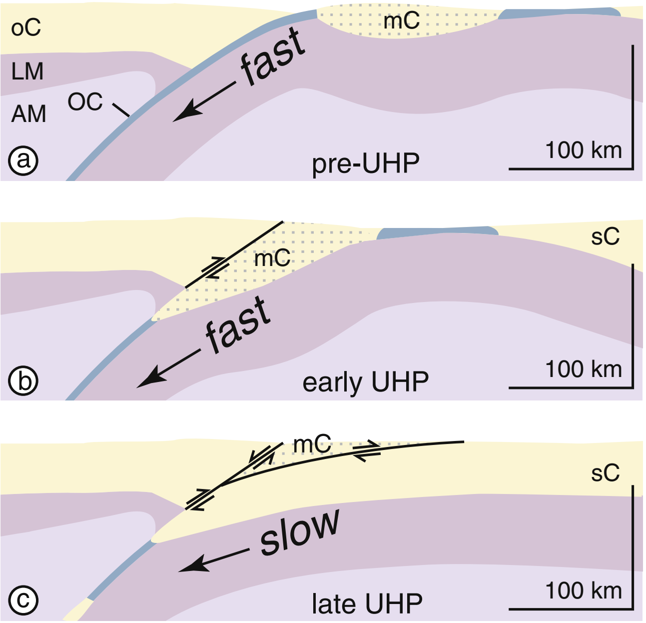

Fig. 2. Two types of UHP terrane formation: early versus late.The transition from oceanic subduction to continental subduction with the intermediate subduction of a microcontinent (mC). a) The oceanic lithosphere exerts a strong pull force, resulting in rapid and steep subduction. b) As a microcontinent (or continental margin) is subducted, buoyancy increases slightly. c) During the subduction of continental crust, buoyancy is greatly increased, reducing the subduction angle and velocity. oC = overriding continent; sC = subducted continent; OC = oceanic crust; LM = lithospheric mantle; AM = asthenospheric mantle.

the entire body internally such that buoyancy forces overcome the boundary tractions (Warren et al., 2008). Furthermore, if the UHP terrane follows the same low-angle path during exhumation as it did during subduction (Ernst and Liou, 2008), larger terranes will take longer to travel vertically.

This 'early vs. mature' hypothesis makes predictions about UHP terrane characteristics:

1) Orogens in which a continental margin has recently begun to subduct, such as the subduction of northern Australia beneath the Banda Arc (Elburg et al., 2004), should have small, actively forming UHP terranes that will be exhumed in a few Myr.
2) Active, mature orogens, such as the Alpine–Himalayan chain, should contain small UHP terranes exhumed rapidly during the early stages of orogeny, and large, buried UHP terranes that formed – or are forming – slowly. The Alpine–Himalayan orogen, where convergence is currently much slower than at the onset of collision (Guillot et al., 2003), does not reveal strong evidence of continental crust at UHP depths (Tilmann et al., 2003), but this does not preclude the presence of an incompletely exhumed UHP terrane in the lower crust (Walsh and Hacker, 2004). That terrane may not reach the surface for another 20 Myr, thus explaining why large UHP terranes are absent from active orogens.
3) Ancient orogens with large, slowly formed UHP terranes should also contain – or at one time have contained – older, rapidly formed, small UHP terranes. The early exposure and small size of early UHP terranes would subject them to more erosion compared to large terranes. The preferential erosion of small terranes would reduce the abundance of ancient small UHP terranes. Nevertheless, some may exist: the ~450 Ma Jämtland HP region (Brueckner and van Roermund, 2007), several hundred km east of the ~425–400 Ma Western Gneiss Region UHP terrane in Norway may be a prime example of a previously subducted continental sliver (as of yet, there is no evidence for UHP). In fact, it was the ~50 Myr age difference between these (U)HP terranes

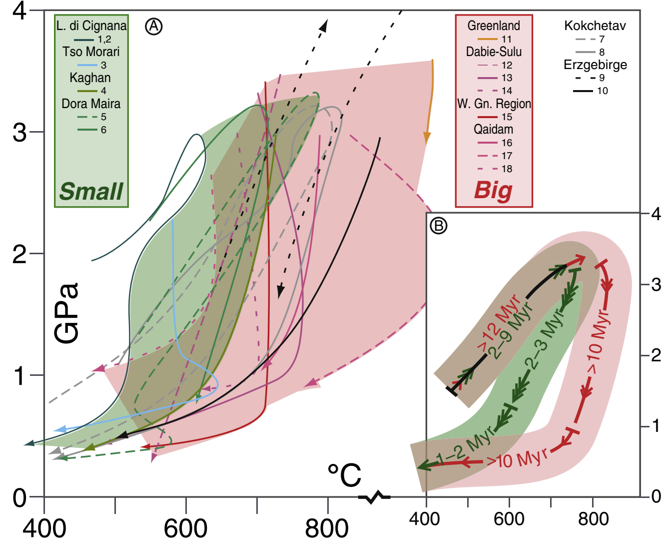

Fig. 3. Pressure–temperature paths of UHP terranes.Large, slowly formed terranes in red/orange define a region (pink) with higher overall temperatures than the small, slowly formed terranes (blue and green). The Kokchetav terrane is not associated with a group and shown in grey. References:1) Van der Klauw et al., 1997; 2) Reinecke, 1998; 3) de Sigoyer et al., 2004; 4) Kaneko et al., 2003; 5) Compagnoni and Rolfo, 2003; 6) Simon and Chopin, 2001; 7) Parkinson, 2000; 8) Zhang et al., 1997; 9) Massonne, 2003; 10) Willner et al., 2000; 11) Gilotti and Krogh Ravna, 2002; 12) Zhang et al., 1995; 13) Nakamura and Hirajima, 2000; 14) Banno et al., 2000; 15) Root et al., 2005; 16) Zhang et al., 2001; 17) Zhang et al., 2005; 18) Song et al., 2003.

that prompted Brueckner and Van Roermund (2004) to coin the term "dunk tectonics," to describe the successive subduction and exhumation of continental slices during a single orogenic cycle. The 'early vs. mature' model predicts that these events occurred at subduction rates successively slowed by increasingly larger volumes of continental material. The Kokchetav and Erzgebirge UHP units may also be good examples of early subducted UHP terranes, but they are poorly exposed, dissected by younger faults (Kokchetav), and have geochronologic data that do not define a coherent picture (see Supplementary Table 1).

The model does not apply directly to UHP terranes that formed in the upper plates of collision zones (e.g., the NEGEP; Gilotti and Krogh Ravna, 2002), we expect those to be similar to other large, slowly formed terranes. The upper plate is thick, and thus buoyant, and, as is the case with Greenland, subducted during the later stages of orogenesis (Gilotti and McClelland, 2007).

3.1. Outstanding questions

The 'early vs. mature' model has limitations in explaining a number of characteristics of UHP terranes, such as the degree of reaction progress (both on the prograde and retrograde path) and the *P–T* paths, as well as the relative abundance and exposure of each end member type of terrane.

Retrogression is ubiquitous in UHP terranes and obscures peak metamorphic conditions. However, even terranes that spent >20 Myr at mantle depths preserve incomplete prograde reactions (Austrheim, 1987; Zhang and Liou, 1997)—presumably governed by fluid availability, deformation, and duration of metamorphism (Mosenfelder et al., 2005). One might expect small UHP terranes to be more retrogressed simply because of their low surface:volume ratio, but this may be compensated by the short time that they spend exhuming. At present, no correlation between degree or type of metamorphic overprint (e.g., greenschist-facies vs. granulite-facies) and terrane size has been noted.

One might also expect that the thermal evolution of the two types of UHP terrane would be different, though no distinction can be drawn from the current dataset (Fig. 3). Heat conduction distance scales with the square root of time ($x \propto 2\sqrt{\kappa t}$), such that a terrane with a subduction/exhumation cycle time of 20 Myr will be less affected by external temperatures if it is more than ~3× thicker than one with a subduction/exhumation cycle time of 2 Myr. This effect is offset by radiogenic heating, however, which would be minor, ~40 °C, for a 3 Myr subduction/exhumation cycle, but significant, 250 °C, for a 20 Myr cycle (these are maxima, assuming no heat loss and a heat production rate of 1 μW/m^3). Thermal-mechanical modeling can help test the proposed model; results thus far have been variable (Gerya et al., 2002; Warren et al., 2008).

As shown in Fig. 1 and Table 1, more small, rapidly evolved UHP terranes have been recognized than large ones. This may be partly attributed to the increased chance for subduction of a microcontinent or continental margin over the subduction of a continental interior. The subduction of thick portions of continental lithosphere may also require a more specific set of requirements – such as a large minimum dimension or a large attached oceanic slab – which, if not met, would otherwise lead to a stall or reversal of subduction and produce only a small UHP terrane. It is also possible that, given the long time that large UHP terranes spend at depth, they are more likely to be overprinted and thus recognized less often. As stated earlier in this section, no correlation between the size of a terrane and the degree of retrogression yet exists. The occurrence of small and large UHP terranes could also simply be related to their size; the current estimate for the total volume of large terranes far exceeds that of small ones. Whereas many small, dissected terranes may form at the onset of continental subduction through the subduction of lobate continental boundaries or microcontinents, once interior portions of continents become subducted, the volume of subducted material is greater.

4. Conclusions

Ultrahigh-pressure terranes define two groups: terranes that are small, thin and subducted and exhumed rapidly, and terranes that are large, thick, and subducted and exhumed slowly. The former may be created during the early stages of continental subduction when the volume of negatively buoyant, subducted oceanic lithosphere, and, thus, forces that pull the subducting lithosphere down prevail; rapid, steep-angle subduction results. The latter may form during the later stages of continent collision when subduction of thick, positively buoyant continental lithosphere leads to slow, gentle-angled subduction. Assessing whether this hypothesis is correct – by looking in detail at both poorly and well studied UHP terranes – is important for understanding large-scale Earth evolution, such as the physical and chemical processes that produced and modified Earth's crust.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2011.12.036.

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