1 Introduction, scope and outline of the thesis

1.1 Introduction

Coesite- and diamond-bearing ultrahigh pressure (UHP) metamorphic crustal rocks have been discovered worldwide in major orogenic belts mainly in the Eurasian continent during the past 30 years (Figure 1.1) (Chopin and Monié, 1984; Smith, 1984; Okay et al., 1989; Wang et al., 1989; Sobolev and Shatsky, 1990; Xu et al., 1992; Caby, 1994; Massonne, 2001; O’Brien et al., 2001; Yang et al., 2001; Ghirebelli et al., 2002; Schmidt et al., 2010; Kotková et al., 2011). This not only provides indisputable evidence that the low density continental crust can be subducted to mantle depths of 80 – 200 km during continent-continent collision and subsequently returned to crustal depths, but also raises new questions: (1) what causes the UHP metamorphic rocks to be exhumed from mantle depths? (2) How and why UHP metamorphic minerals are preserved rather than being destroyed during the long history of subduction and exhumation? For this reason, the kinematics and dynamics of orogenesis, as well as the relationship between UHP metamorphism and orogenic processes have received much interest of the geoscientists all over the world (Platt, 1993; Liou et al., 1994; Davies and von Blanckenburg, 1995; Ernst, 2001; Zheng, 2008).

Figure 1.1 Global distribution and metamorphic age of coesite- and diamond-bearing UHP metamorphic terranes recognized in the world (modified after Liou et al., 1994; Zheng, 2008; Dobrzhinskaya, 2012)

* This chapter was part of the Chinese version of the thesis.
INTRODUCTION

Continental subduction and crustal exhumation are two fundamental tectonic processes during the evolution of a collisional orogen, for which evidence can be found back in many orogenic belts (England and Molnar, 1990; Ernst et al., 1997). Therefore, recognition and understanding of metamorphic processes during the subduction and exhumation of continental crust are important since they control the $P$-$T$ conditions for the formation of UHP metamorphic mineral assemblages, the timing of lithospheric thickening, the thermal history of the evolving crust in continental subduction zones and the accretionary history of the collisional continents/blocks (Dobretsov et al., 1995; Hacker et al., 2000; Rubatto and Hermann, 2001; Chopin, 2003; Hacker et al., 2004; Ernst, 2006; Zheng, 2008).

Asia, especially China, possesses the most remarkable abundance of UHP collisional orogenic belts/rocks on Earth (Figure 1.1 and Figure 1.2). In east-central China, the Triassic Dabie-Sulu orogenic belt crops out as the world’s largest and perhaps best-exposed unit of UHP metamorphic rocks (Wang et al., 1990; Okay et al., 1993; Hacker et al., 1998; Zhang et al., 2009c). In addition, there are the well-known early Paleozoic north Qaidam-south Altyn metamorphic terranes (Yang et al., 2001) and the late Paleozoic southwest Tianshan belts (Zhang et al., 2005b; Lü et al., 2008) in the northwest of China; the early Paleozoic north Qinling belt in the central of China (Hu et al., 1994; Yang et al., 2002a) and the Cenozoic Himalayan belt in the northwest of Pakistan (O’Brien et al., 2001).

These UHP metamorphic rocks and their retrogressed equivalents are volumetrically minor components of orogenic belts formed by collisional processes, but they provide invaluable information about continental collision/subduction and lithospheric exhumation. Furthermore, by taking these UHP rocks as “natural laboratories”, geoscientists around the world have carried out extensive studies with regard to fluid transport, genesis of arc magmas, element mobility, and geodynamic mechanisms responsible for the growth and

Figure 1.2 Distribution of coesite- or diamond-bearing UHP metamorphic terranes in China (modified after Yang et al., 2005)
CHAPTER 1

destruction of continents (Zheng et al., 2003; 2004; Yin, 2006; Agard et al., 2009; Zheng et al., 2011a; Wu and Zheng, 2013; Song et al., 2014). By calculating the metamorphic peak conditions and characterizing the retrograde P-T paths of these HP/UHP metamorphic rocks, an “educated guess” can be made regarding the subduction depth and possible mineral-chemical changes that occurred during exhumation. In combination with geochronological data, this approach allows for the spatial and temporal understanding of the physical and chemical processes involved in the formation and evolution of an orogenic belt.

Here, in the present study, the north margin of Qaidam Orogen, part of the Central Orogenic Belt of China (COBC) (Jiang, 1993; Yang et al., 2002a; 2005) is the focus of our research (Figure 1.2 and Figure 1.3). The northern margin of the Qaidam orogen has been recognized as an UHP metamorphic belt since coesite as inclusions in zircon separates from pelitic gneiss were first reported over 10 years ago (Yang et al., 2001). This belt was formed as a result of the convergence and continental collision of the Qilian, the Qaidam and the Alxa terranes during the early Paleozoic (Yin and Harrison, 2000), and extends along a NW-SE-striking belt with a total length of over 400 km from Dulan in the east to Da Qaidam (Yuka) in the west (Figure 1.3).

As yet, in the north Qaidam orogen, the subduction/exhumation mechanisms, exhumation/uplift rates and cooling histories of the UHP metamorphic rocks are not completely understood and resolved so far, due to the complicated metamorphic history and the lack of appropriate age constraints on the mechanisms of exhumation. The $^{40}$Ar/$^{39}$Ar isotope dating technique is widely applied to date metamorphic events and associated deformation events by assessing the cooling and exhumation history of orogenic belts. The fact that different minerals have different closure temperatures, it has become possible to date the last cooling age through a specific closure temperature of a range of minerals with different closure temperatures, which potentially allows the reconstruction of the cooling history of a rock unit (Dodson, 1973; McDougall and Harrison, 1999; Di Vincenzo and Palmeri, 2001; Wilke et al., 2010; Hacker et al., 2011; Warren et al., 2012b).

1.2 Scope of the thesis

The North Qaidam UHP metamorphic belt is generally divided into four distinct terranes on the basis of spatial relations, rock association and petrologic criteria. From east to west, they are the Dulan eclogite-gneiss terrane (DLT), the Xitieshan eclogite-gneiss terrane (XTT), the Luliangshan garnet-peridotite terrane (LLT) and the Yuka eclogite-gneiss terrane (YKT). These terranes are separated by Paleoozoic to Cenozoic sediments (Figure 1.3). Since the first report of coesite-bearing pelitic gneiss from the Dulan terrane over a decade ago (Yang et al., 2001), petrological indicators or exsolution textures of UHP metamorphism were recognized and confirmed in the Luliangshan (Song et al., 2004a; 2005a), the Yuka (Zhang et al., 2009a) and the Xitieshan (Liu et al., 2012) terranes in succession. These imply that the northern
INTRODUCTION

margin of Qaidam Basin is a typical continental subduction-collision complex exhumed from > 80-100 km in depths. In this thesis, we put our attentions to two key localities: the Yuka terrane and the Xitieshan terrane.

Figure 1.3 A sketched geological map of the northern Qaidam Mountains (modified after Zhang et al., 2005a)

The Yuka terrane is located in the most western segment of the North Qaidam UHP metamorphic belt, the northern flank of the Lüliang Mountains and 40 km north of Da Qaidam town (Figure 1.3). Several studies report significant progress with regard to our understanding of the petrology, geochemistry and geochronology of these extraordinary UHP metamorphic rocks since the first report of eclogite by Yang et al. (1998):

1. Two types of eclogite can be recognized: coarse-grained phengite eclogite and fine-grained massive eclogite (Lu et al., 1999; Yang et al., 2001; Chen et al., 2005; Zhang et al., 2005a). Moreover, coesite-inclusions within a garnet porphyroblast were identified from the coarse-grained eclogite (Zhang et al., 2009a).

2. A detailed P-T path has been determined for coesite eclogite based on garnet-clinopyroxene thermometry and garnet-clinopyroxene-phengite-quartz barometry, and obtained the peak P-T condition as $P = 23 – 34$ kbar and $T = 600 – 730^\circ$C (Chen et al., 2005; Zhang et al., 2005a; Zhang et al., 2009a).

3. The relationship between eclogites and country rocks in Yuka area was confirmed as “in situ” rather than “tectonic emplacement” contacts based on detailed petrological and mineralogical studies, as well as P-T paths comparison (Zhang et al., 2004).

4. It was noted that the protoliths of the Yuka eclogites are within-plate basalt (WPB), enriched-type middle-ocean ridge basalts (E-MORB) and ocean island basalt (OIB) which
probably formed in a continental rift or incipient oceanic basin setting during the dispersal of Rodinia super-continent (Yang et al., 2006; Chen, 2007; Song et al., 2010).

5. Geochronological studies have been conducted on the HP/UHP mafic rocks and host-rocks by various techniques (e.g., zircon U-Pb, $^{40}$Ar/$^{39}$Ar and Sm-Nd). The timing of eclogite-facies metamorphism were restricted into two groups: $488 - 495$ Ma (zircon U-Pb TIMS, Zhang et al., 2005a) and $436 - 443$ Ma (zircon U-Pb LA-ICP-MS, Chen et al., 2009a; Song et al., 2010; Xiong et al., 2012).

The Xitieshan terrane, in the central segment of the North Qaidam UHP Orogenic belt, is around $80$ km SE of the Yuka terrane (Figure 1.3). Eclogite was first reported and detailed studied simultaneously by Zhang et al. (2002) and Yang et al. (2002b). However, coesite was recognized only recently as an inclusion in a metamorphic zircon from a garnet amphibolite (Liu et al., 2012). During the past ten years, major contributions have been achieved on the following aspects:

1. Recognition of bi-mineralic and phengite-bearing eclogites from mafic boudins in this terrane (Yang et al., 2005; Zhang et al., 2011a). Meanwhile, coesite pseudomorphs in omphacite and coesite inclusions in zircon were discovered and confirmed in these mafic rocks in succession (Zhang et al., 2011a; Liu et al., 2012).

2. Confirmation of the mutual relationship between the eclogites and their host gneisses that are characterized by “in situ” rather than “tectonic relationship” (Zhang et al., 2006).

3. Calculation of values for the peak eclogite-facies $P$-$T$ conditions as $P = 27.1 – 31.7$ kbar, $T = 730 – 830$ °C based on garnet-clinopyroxene-phengite geobarometry (Zhang et al., 2005a; Zhang et al., 2011a) and the $P$-$T$ conditions for granulite-facies overprinting as $P = 10 – 14$ kbar, $T = 750 – 865$ °C based on garnet- clinopyroxene- plagioclase- quartz geobarometer (Zhang et al., 2005a). Medium-pressure granulite metamorphism $P$-$T$ conditions found in paragneisses as $P = 6.7 – 8.6$ kbar, $T = 705 – 800$ °C by utilizing garnet-biotite thermometry and the GASP geobarometer (Zhang et al., 2008a).

4. Protolith ages of the Xitieshan eclogite and their host granitic gneiss were constrained at $750 – 877$ Ma (Zhang et al., 2006; Zhang et al., 2011a; Xiong et al., 2012) and $890 – 952$ Ma (Meng et al., 2005; Zhang et al., 2006; 2008a; Zhang et al., 2012), respectively. The age of eclogite-facies metamorphism was inferred at $480 – 495$ Ma (zircon TIMS and SHRIMP U-Pb dating) (Zhang et al., 2005a) and $432 – 461$ Ma (zircon SIMS, SHRIMP and LA-ICP-MS U-Pb dating) (Song et al., 2011; Zhang et al., 2011a; Liu et al., 2012).

In previous studies, especial geochronological studies as yet the focus was mainly on the UHP metamorphic eclogites by applying zircon U-Pb dating with various methods (SHRIMP, LA-ICPMS, SIMS and TIMS methods) and thus to constrain the age of peak UHP metamorphism. Hence, we present further detailed thermal-geochronological analyses on representative minerals from both eclogites and their country rocks to afford new critical constraints to temperature-time (T-t) paths for these HP/UHP metamorphic rocks.

In this thesis, we present chemistry and laser stepwise heating $^{40}$Ar/$^{39}$Ar analyses of amphibole, phengite/muscovite, biotite and K-feldspar from the eclogites, garnet
amphibolite/amphibolites, gneisses and schists of two key localities, Yuka and Xitieshan terrane, North Qaidam Orogen. Further, we also carried out in vacuo crushing and stepwise heating $^{40}$Ar/$^{39}$Ar analyses on metamorphic amphibole and quartz veins in HP/UHP rocks from Yuka terrane. Combined with previous published U-Pb data, we attempt to:

1. Constrain the cooling and exhumation history of the UHP metamorphic rocks to upper-crustal depths based on the new $^{40}$Ar/$^{39}$Ar analyses and the reasonably well-known isotopic closure temperatures in different minerals;
2. Decipher the genesis of extraneous $^{40}$Ar with regard to UHP metamorphic minerals;
3. Address the origin of fluid flow and constrain the age of quartz veining in a direct approach.

1.3 Outline of the thesis

This thesis consists of nine chapters: Introduction, scope and outline of the thesis (Chapter 1), Geological background (Chapter 2), Petrography of HP/UHP rocks in the Yuka terrane (Chapter 3), $^{40}$Ar/$^{39}$Ar geochronology in the Yuka terrane (Chapter 4), $^{40}$Ar/$^{39}$Ar in vacuo crushing and stepwise heating of Yuka amphiboles (Chapter 5), $^{40}$Ar/$^{39}$Ar in vacuo crushing of Yuka veins (Chapter 6), Petrography of HP/UHP rocks in the Xitieshan terrane (Chapter 7), $^{40}$Ar/$^{39}$Ar geochronology in the Xitieshan terrane (Chapter 8), and Synthesis (Chapter 9).

Chapter 2 describes the main tectonic feature and their important characteristics of the North Qaidam Orogen. The geological background of the study areas: Yuka and Xitieshan terranes are also described in this chapter. Chapter 3 of this Thesis focuses on the petrography, mineral chemistry and $P$-$T$ conditions of ultra-high pressure (UHP) rocks in the Yuka terrane, North Qaidam. Chapter 4 gives new $^{40}$Ar/$^{39}$Ar geochronological data on amphiboles, white micas and K-feldspar in the Yuka terrane. This chapter also provides information on the genesis of extraneous $^{40}$Ar with regard to UHP metamorphic minerals and the cooling/exhumation history of the UHP metamorphic rocks in Yuka terrane. Chapter 5 focuses on the occurrence of extraneous $^{40}$Ar in Yuka retrograde metamorphic amphiboles which is investigated by joint $^{40}$Ar/$^{39}$Ar in vacuo crushing and stepwise heating. Chapter 6 gives a preliminary investigation of fluid inclusions in quartz and a direct $^{40}$Ar/$^{39}$Ar dating by in vacuo crushing of quartz veins in HP/UHP rocks from Yuka terrane. Chapter 7 presents the petrography, mineral chemistry and $P$-$T$ conditions of the ultra-high pressure rocks in the Xitieshan terrane, North Qaidam. Chapter 8 contains an overall $^{40}$Ar/$^{39}$Ar thermochronological data on the retrogression and exhumation of the ultrahigh pressure (UHP) metamorphic rocks from Xitieshan terrane. Chapter 9 is the synthesis of the research project. Chapter 4, 5, 6 and 8 of this thesis are relatively independent as separated articles, which have been submitted or are in press. This leads to some unavoidable repetitions, especially concerning regional geology/setting and tectonic conclusions.

Appendices describe all analytical methods used in this study.
CHAPTER 1

Mineral abbreviations used in this thesis after Whitney and Evans (2010) except for Sym – symplectite (see Table 1.1).

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Mineral</th>
<th>Abbreviation</th>
<th>Mineral</th>
<th>Abbreviation</th>
<th>Mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ab</td>
<td>Albite</td>
<td>Di</td>
<td>Diopside</td>
<td>Phl</td>
<td>Phlogopite</td>
</tr>
<tr>
<td>Alm</td>
<td>Almandine</td>
<td>Ep</td>
<td>Epidote</td>
<td>Pl</td>
<td>Plagioclase</td>
</tr>
<tr>
<td>Amp</td>
<td>Amphibole</td>
<td>Fsp</td>
<td>Feldspar</td>
<td>Ph</td>
<td>Phengite</td>
</tr>
<tr>
<td>Adr</td>
<td>Andradite</td>
<td>Grs</td>
<td>Grossularite</td>
<td>Prp</td>
<td>Pyrope</td>
</tr>
<tr>
<td>Ap</td>
<td>Apatite</td>
<td>Grt</td>
<td>Garnet</td>
<td>Qz</td>
<td>Quartz</td>
</tr>
<tr>
<td>Bar</td>
<td>Barroisite</td>
<td>Jd</td>
<td>Jadeite</td>
<td>Rt</td>
<td>Rutile</td>
</tr>
<tr>
<td>Bt</td>
<td>Biotite</td>
<td>Kfs</td>
<td>K-feldspar</td>
<td>Sps</td>
<td>Spessartine</td>
</tr>
<tr>
<td>Chl</td>
<td>Chlorite</td>
<td>Ky</td>
<td>Kyanite</td>
<td>Ttn</td>
<td>Titanite</td>
</tr>
<tr>
<td>Cpx</td>
<td>Clinopyroxene</td>
<td>Ms</td>
<td>Muscovite</td>
<td>Zrn</td>
<td>Zircon</td>
</tr>
<tr>
<td>Czo</td>
<td>Clinozoisite</td>
<td>Omp</td>
<td>Omphacite</td>
<td>Zo</td>
<td>Zoisite</td>
</tr>
</tbody>
</table>