Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Asian Earth Sciences 28 (2006) 160–173
Journal of Asian Earth Sciences
www.elsevier.com/locate/jaes

Timing and mechanism of formation and exhumation of the Northern Qaidam ultrahigh-pressure metamorphic belt

Xu Zhiqin *, Yang Jingsui, Wu Cailai, Li Haibing, Zhang Jianxin, Qi Xuexiang, Song Shuguang, Qiu Haijun

Laboratory of Continental Geodynamics, Institute of Geology, Chinese Academy of Geological Sciences, Baiwanzhuang Road 26, Beijing 100037, China

Received 10 October 2004; received in revised form 20 January 2005; accepted 14 September 2005

Abstract

The Qilian Caledonian orogenic belt on the north margin of the Qinghai-Tibet Plateau were formed by convergence and collision of the Alxa terrain, Qilian terrain and Qaidam terrain. The 350-km-long, WNW–ESE-trending North Qaidam ultrahigh-pressure (UHP) metamorphic belt, lying between the Qilian and Qaidam terrains, was formed between 495 and 440 Ma by deep subduction of the South Qilian Sea and the Qaidam continental crust beneath the Qilian terrain. The UHP belt was exhumed by a process of 'oblique extrusion' during transformation from 'normal' to 'oblique' intracontinental subduction between the Qilian and Qaidam terrains. Exhumation began at 470–460 Ma and was completed by 406–400 Ma. Exhumation structures are well-preserved in the UHP rocks and record extensive retrograde metamorphism.

Keywords: Northern Quaidam; UHP metamorphic belt; Exhumation; Mechanism

1. Introduction

The northern Qinghai-Tibet plateau (NQTP) is a mosaic of multiple terrains and island/continental arcs. The NQTP composite terrain is composed of the Qilian terrain, Qaidam terrain, northern part of the eastern Kunlun terrain, southern part of the eastern Kunlun terrain and Altyn terrain. Lying in the northern margin of the Qinghai-Tibet Plateau, the Qilian Caledonian orogenic belt form a WNW–ESE trending belt about 800 km long and 400 km wide (Fig. 1). This belt is bounded on the north by the Hexi Corridor, on the south by the Qaidam basin, on the east by the West Qinling Mountains and on the west by the Altyn Tagh fault. It is considered to be the product of convergence and collision of the Alxa terrain (west segment of the North China plate), the Qilian and the Qaidam terrain during the Caledonian. Subduction complexes along both sides of the Qilian terrain separate the three terrains (Xu et al., 2000). Late Devonian molasse deposits rest unconformably on the Lower Palaeozoic folded metamorphic rocks and Caledonian granites, indicating the end of the Caledonian orogeny.

The subduction complex between the Alxa and Qilian terrains consists of ophiolites, mélange and high-pressure (HP) metamorphic rocks (Xiao et al., 1978; Wu et al., 1993). The North Qilian continental arc complex to the north, combined with an accretionary wedge, records an active continental- margin accretionary system on the southern margin of the Alxa terrain (Xu et al., 1994; Xia and Xia, 1991; Xia et al., 1998; Zhang and Xu, 1995). Geochronological studies on the timing of either formation or peak metamorphism for the HP or magmatic rocks from these terrains by using various radiometric methods yielded the following results: (1) gabbros from the ophiolite of the northern Qilian indicating the North Qilian sea have a SHRIMP U/Pb zircon age of 500 ± 17 Ma (Shi et al., 2004), and the HP eclogites have SHRIMP U/Pb zircon age of 463–468 Ma representing the North Qilian sea was subducted to a depth of at least 60 km (Song et al., 2004). These ages are earlier than the formation age (440–460 Ma) of the blue schist (Wu et al., 1993; Xu et al., 1994; Zhang and Xu, 1995). (2) The northern Qilian volcanic arc formed at 486–438 Ma and the marine volcanic rocks at a back-arc spreading ridge formed at 469–454 Ma (Xu et al., 2000).

The Caledonian arc-trench-basin system distribution and ductile thrust structures with south- to southwest-directed polarity in the North Qilian active continental margin

* Corresponding author.
E-mail address: xzq@ccsd.cn (X. Zhiqin).

1367-9120/$ - see front matter
doi:10.1016/j.jseaes.2005.09.016

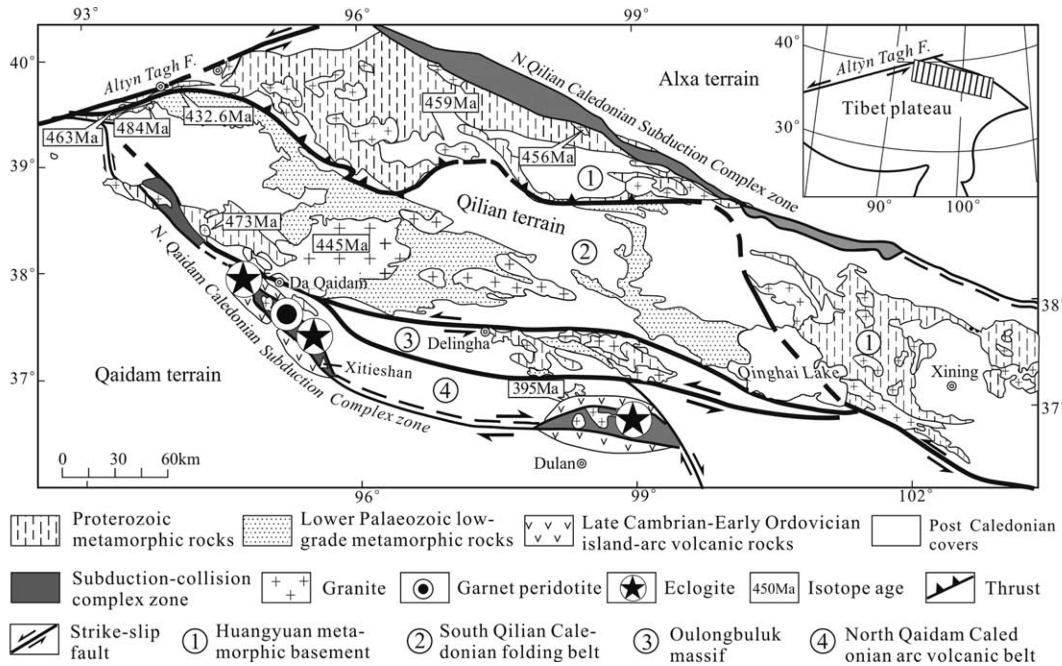

Fig. 1. Tectonic map of the Qilian terrain and the northern Qaidam area.

between the Alxa terrain and the Qilian terrain suggest that the North Qilian Sea was subducted northward or northeastward beneath the Alxa terrain (Cui et al., 1996; Xu et al., 2000).

Recently, an ultrahigh-pressure (UHP) belt, 350 km long and 10 km wide, named the north Qaidam UHP metamorphic belt, was found in the Da Qaidam -Xitieshan -Dulan area between the Qilian and Qaidam terrains (Yang et al., 1998, 2000, 2001; Zhang et al., 1999, 2000a,b). Coesite inclusions in zircon from garnet-bearing muscovite gneiss that hosts the Dulan eclogite (Yang et al., 2001) demonstrate that the belt formed by deep subduction of continental crust. Estimated conditions of the peak UHP metamorphism are $P \geq 2.8$ GPa and $T \geq 700$–800 °C.

The study shows that volcanic rocks of the Tanjianshan Group on the northern margin of the Qaidam terrain are island-arc in character and inferred the existence of a major tectonic boundary between the two terrains. LA-ICP-MS U/Pb analyses on zircons from a tholeiite of the northern Qaidum volcanic arc yielded an age of 514.2 ± 8.5 Ma (Shi et al., 2004). U/Pb zircon and SHRIMP U/Pb zircon ages on the cal-alkaline volcanic rocks have ages from 496 to 440 Ma (Li et al., 1999; Wu et al., 2001). In summary, these analyses show that the ophiolite representing the south Qilian oceanic basin has an age of about more than 514 Ma, and the subduction of this oceanic basin and formation of the volcanic arc complex occurred at about 500–440 Ma.

Previous studies have shown that the Qilian terrain and the Altyn terrain which are on either side of the Altyn Tagh strike-slip fault have similar structures, age of formation, and compositions. In particular, the northern Qilian HP belt and northern Qaidam UHP belt can be correlated with the northern Altyn HP belt and the southern Altyn UHP belt (Liu et al., 1996; Zhang et al., 2001), respectively. Correlation of these two belts suggests a left-lateral offset of at least 400 km on the Altyn Tagh Fault (Xu et al., 1999).

In this paper, mainly through an intensive study of the Caledonian tectonic system of the Qilian terrain, we further confirm the existence and nature of the terrain boundary and reveals the formation mechanism of the northern Qaidam UHP metamorphic belt, and through a study of the tectonic styles and geometric and kinetic characteristics formed in the process of exhumation of the UHP metamorphic belt and its geochronology, we analyze the mechanism of exhumation and timing of the belt and present a model for its formation and exhumation.

2. Caledonian tectonic system of the Qilian terrain and the northern Qaidam UHP metamorphic belt

2.1. Caledonian tectonic units of the Qilian terrain

The Qilian terrain, about 600 km long and 240 km wide, is located between the Alxa and Qaidam terrains. Its northern and southern boundaries, respectively, are the northern Qilian subduction complex and the northern Qaidam subduction complex. From north to south, the Caledonian tectonic units of the terrain may fall into four parts: (1) the Huangyuan metamorphic basement, (2) the South Qilian Caledonian fold belt, (3) the Oulongbuluk block, and (4) the northern Qaidam Caledonian volcanic island-arc zone (Fig. 1).

2.1.1. Huangyuan metamorphic basement

The Huangyuan metamorphic basement is mainly distributed in the northern part of the Qilian terrain. It is composed of 900–1000 Ma high-grade metamorphic series (high amphibolite facies) and its overlying greenschist-facies metamorphic series. Study suggests that the Huangyuan metamorphic basement is similar to those of the northern Qaidam, Qaidam terrain and Yangtze block, being the basement that developed during the formation of the supercontinent Rodinia in the Jinningian period at 900–1000 Ma (Wan et al., 2000). The metamorphic basement is superimposed by the Caledonian metamorphic event (Nd–Sm age 396–567 Ma) (Juang and Sun, 2002) and intruded by Caledonian granite, suggesting that the Huangyuan metamorphic basement was reactivated in the Caledonian period and involved in the Caledonian orogeny. In addition, several ophiolite zones and ultramafic zones occur at Lajishan in the eastern part and Danghe Nanshan in the western part of the Huangyuan metamorphic basement.

2.1.2. South Qilian Caledonian fold belt

The South Qilian Caledonian fold belt is located in the southern part of the Huangyuan metamorphic basement, where Cambrian–Ordovician strata are widespread. Cambrian–Ordovician strata, which consist of lava flows, pyroclastic rocks and abyssal and bathyal deposits, contain both 'Southeast China type' and 'transition-type' faunas. Silurian sedimentary rocks and Early Silurian graptolite faunas belong to the 'Southeast China' type (Bureau of Geology and Mineral Resources of Qinghai Province, 1991). This flysch series was strongly folded in the Caledonian orogeny, resulting in the formation of tight upright folds accompanied by flow cleavages in argillaceous rocks and gentle upright folds accompanied by fracture cleavages or spaced cleavages in arenaceous rocks, and are intruded by late Caledonian granites.

2.1.3. Oulongbuluk block

The Oulongbuluk block in the southern part of the Qilian terrain is composed of the granulite facies and amphibolite facies rocks of the Daken Daban Group (Zhang et al., 2001). It mainly formed at 900–1000 Ma (Wan et al., 2000). Overlying the metamorphic basement are Sinian to Ordovician covers, and platform-type sediments containing typical 'North China-type' faunas occur in Cambrian–Ordovician strata composed of limestone and phyllite (Bureau of Geology and Mineral Resources of Qinghai Province, 1991), implying that the Oulongbuluk block may possibly be a block divorced from the Alxa terrain. Sinian to Ordovician strata suffered Caledonian folding and thrusting. The tectonic styles in the Cambrian–Ordovician strata are manifested by the gradual transformation from syncleavage folds with a north-dipping axial plane to recumbent folds from north to south. These folds are accompanied by ductile thrusts with southward shearing and intruded by late Caledonian granite. The features of Caledonian tectonic deformation in this block show the southward orogenic polarity and its boundaries are constrained by two ductile sinistral strike-slip shear zones formed at 240–250 Ma (Xu et al., 2002).

2.1.4. Northern Qaidam Caledonian volcanic island-arc zone

On the southern margin of the Qilian terrain, the greenschist-facies volcanic and volcaniclastic rocks of Tanjianshan and Shaliuhe Groups (Bureau of Geology and Mineral Resources of Qinghai Province, 1991) extend intermittently for nearly 400 km along the belt and are accompanied by a subduction complex. It is very narrow, being only more than 10 km wide. The volcanic rocks are unconformably overlain by Late Devonian molasse deposits.

Recently, through a study of the volcanic rocks of the Tanjianshan Group in the northern Qaidam marginal area it has been indicated that the volcanic rocks belong to the calc-alkaline series. They are characterized by enrichment of LREE and their trace element distribution patterns are similar to those of Pearce's island-arc volcanic rocks. This indicates that these Early Paleozoic volcanic rocks are island-arc tholeiite and that the tectonic environment of the volcanic rocks should belong to the volcanic island-arc one (Shi et al., 2004). Moreover, the gabbro intruded into the Tanjianshan Group has a zircon U–Pb age of 496.3 ± 6.3 Ma (Yuan et al., 2002) and the island-arc tholeiite and intermediate-acid volcanic rocks of the same group have zircon U–Pb ages of 514.2 ± 8.5 Ma by LA-ICP-MS analysis (Shi et al., 2004) and 486 ± 13 Ma, respectively (Li et al., 1999), implying a Late Cambrian–Early Ordovician age for the volcanic island arc produced by subduction of the south Qilian sea.

A suite of I-type monzodiorite-quartz monzodiorite–granodiorite–monzogranite of calc- alkaline affinity also occurs along the Aulaoshan–Luliangshan area, west segment of the northern Qaidam zone, exhibiting marked negative Th and Nb anomalies as well as positive P, Ti and Ba anomalies, features typically of I-type island-arc granitic rocks (Wu et al., 2000, 2001).

Both the I-type granites and volcanic rocks were formed at an active continental margin during subduction of the South Qilian Sea. The subducted sea crust was metamorphosed from greenschist facies through amphibolite facies to eclogite facies. Dehydration of the crust during metamorphism expelled fluids into the overlying mantle wedge, causing partial melting to form the island arc lavas and I-type granites.

2.2. Northern Qaidam UHP metamorphic belt

The northern Qaidam UHP belt is intimately associated with Cambrian–Ordovician island-arc volcanic rocks and intruded by Caledonian granites. It extends discontinuously for 350 km and is the most important component part of the northern Qaidam Caledonian subduction complex zone. This UHP metamorphic belt is comprised of eclogite, coesite-bearing gneiss and garnet peridotite. Metamorphic conditions varied between the eastern and western segments of the belt. In the west, the Da Qaidam eclogite formed at temperatures of 620–730 °C and pressures of 2.3–2.8 GPa and the Xitieshan eclogite at 810–850°C and >1.4 GPa. In the eastern segment, the eclogite was formed at temperatures of 610–680 °C and pressures of 2.6 GPa. The presence of coesite in the garnet–muscovite gneiss in Dulan, which hosts the eclogites, indicates that it reached temperatures of 700 °C and pressures of 2.8 GPa (Yang et al., 1998, 2000; Zhang et al., 2001). The presence of coesite in these rocks provides strong evidence that the supercrustal rocks were subducted to a depth of at least 100 km (Liou et al., 1994; Coleman and Wang, 1995).

The Dulan UHP metamorphic rocks have zircon SHRIMP age ranging between 495 and 465 Ma and Sm–Nd ages of 496–444 Ma. The Da Qaidam garnet peridotite has zircon SHRIMP ages of 497–436 Ma and the Da Qaidam eclogite formed at 495 Ma (Yang et al, 1998, 2000, 2002; Zhang et al., 2000a,b). These dates indicate that the northern Qaidam UHP belt formed approximately at 495–440 Ma.

2.3. Caledonian tectonic regime of the Qilian terrain and formation of the northern Qaidam UHP metamorphic belt

Based on the above analysis, we make the following preliminary observations of the Caledonian plate regime for the Qilian terrain.

(1) According to the composition of the Qilian terrain, it may be found that the Qilian terrain is composed of several small blocks. To the north lies the Huangyuan metamorphic block, to the south is the Oulongbuluk block composed of the metamorphic basement and Lower Paleozoic 'North China-type' platform deposits, and in the center is the abyssal-bathyal sea basin composed of Lower Paleozoic (Cambrian–Silurian) flysch deposits, containing 'South China-type' faunas.

(2) In the southern part of the terrain there is an island-arc volcanic–magmatic zone, which formed in Late Cambrian–Early Ordovician. It is inferred that its formation was related to the northward subduction of the South Qilian Sea. It is an accretional island-arc terrain resulting from subduction. A thick (>3000 m) sequence of mid-late Ordovician–Silurian (460–410 Ma) flysch crops out extensively in the northern part of UHP belt. It consists of sandy slate, phyllite and intermediate-basic volcanic rocks, representing deposits formed in a back-arc basin.

(3) On the convergent boundary between the Qilian and Qaidam terrains, there occurs the northern Qaidam Caledonian subduction complex zone, which is composed of ophiolites and UHP metamorphic rocks. The northern Qaidam ophiolite consists of peridotite, gabbro, cumulates and diabase–gabbro dike swarms (Xia et al., 1998; Yang et al., 2000). Xia et al. (1998) thought that the northern Qaidam ophiolite represents the tectonic environment of the South Qilian Sea and formed in the Early-Middle Cambrian. Therefore it is inferred that the North and South Qilian seas may have been linked and that the terrain occurred in the same Sea.

(4) Coesite was found in eclogite-bearing country rocks–garnet–muscovite gneiss-in Dulan (Yang et al., 2001), suggesting that the UHP metamorphic rocks are the product of deep subduction of continental crust. The UHP rocks formed at 495–440 Ma BP, after the formation of the island-arc volcanic–magmatic zone accompanying the subduction of oceanic crust. As now no exact evidence indicates that the protoliths of the UHP rock were a (relic) component of the Early Paleozoic south Qilian Sea. Therefore, there is a possibility that the UHP metamorphic slices formed by the deep subduction of Sea crust beneath the South Qilian may have been 'delaminated' down and not have been exhumed or may have been exhumed but not have been found. Later, the continental crust of the Qaidam terrain continued to be subducted to very great depths to form the North Qaidam UHP metamorphic zone.

(5) The Caledonian tectonic deformation of the Lower Paleozoic strata in the south-central part of the Qilian terrain is manifested by the features of south-directed polarity: the deformation changes from upright folds → south-overturned congruous folds → recumbent folds from north to south, accompanied by southward ductile thrusts. This provides tectonic evidence for the northward subduction of the Qaidam terrain beneath the Qilian terrain.

3. Exhumation structures of the northern Qaidam UHP Terrain

The principal structures preserved in the northern Qaidam UHP metamorphic belt were formed during exhumation. Structures formed during the subduction stage are only rarely preserved because of the extensive retrograde metamorphism. In this section, we discuss the structural styles, mechanisms, and timing of exhumation in the northern Qaidam terrain.

The northern Qaidam UHP metamorphic belt may be divided into an eastern segment (north Dulan UHP metamorphic zone) with striking NW–SE and 10 km of width, and a western segment (Da Qaidan -Luliangshan–Xitieshan UHP metamorphic zone) with striking E–W and exceeding 3–5 km of width.

3.1. Structural features of the Dulan segment

The Dulan UHP metamorphic zone is located at the Yematan-Shaliuhe area of Dulan, eastern segment of the North Qaidam UHP belt. It is accompanied with the late Cambrian–early Ordovician island arc volcanic rocks and intruded by Late Caledonian granites. Late Devonian molasse deposits rest unconformably on the island arc volcanic rocks at the south. The east extending of the Dulan UHP zone is cutting off by a NNW–SSE striking fault (Fig. 2a).

The Dulan UHP rocks consist chiefly of K-feldspar-plagioclase gneiss, biotite-K-feldspar-plagioclase gneiss, plagioclase gneiss, granitic gneiss, coesite-bearing garnet–muscovite–plagioclase gneiss, amphibolite, K-feldspar-plagioclase schist, felsic biotite schist, jadeite quartzite, taurolite-bearing garnet–biotite–plagioclase gneiss, kyanite-bearing biotite-plagioclase gneiss, kyanite-bearing two-mica-quartz schist, two-mica-quartz schist and marble. There are many nodules and lenses of gabbro, diabase, serpentinized harzburgite, dunite, eclogite and garnet amphibolite in the gneiss and schist. During exhumation, the rocks underwent retrograde metamorphism, which is expressed as: (1) $Omp \rightarrow Cpx + Pl$ $(Ab > 75\%)$, (2) $Omp + H_2O \rightarrow Amp + Ab$, (3) $Omp + Grt + H_2O \rightarrow Amp + Pl$, (4) $Phe + Qtz + Ca^{2+} + Na^{+} \rightarrow Bi + Pl$, and (5) $Rt + Al^{3+} + Ca^{2+} \rightarrow Spn$ (The abbreviation of mineral names after Kretz, 1983). These reactions suggest that the rocks were first retrograded under amphibolite facies

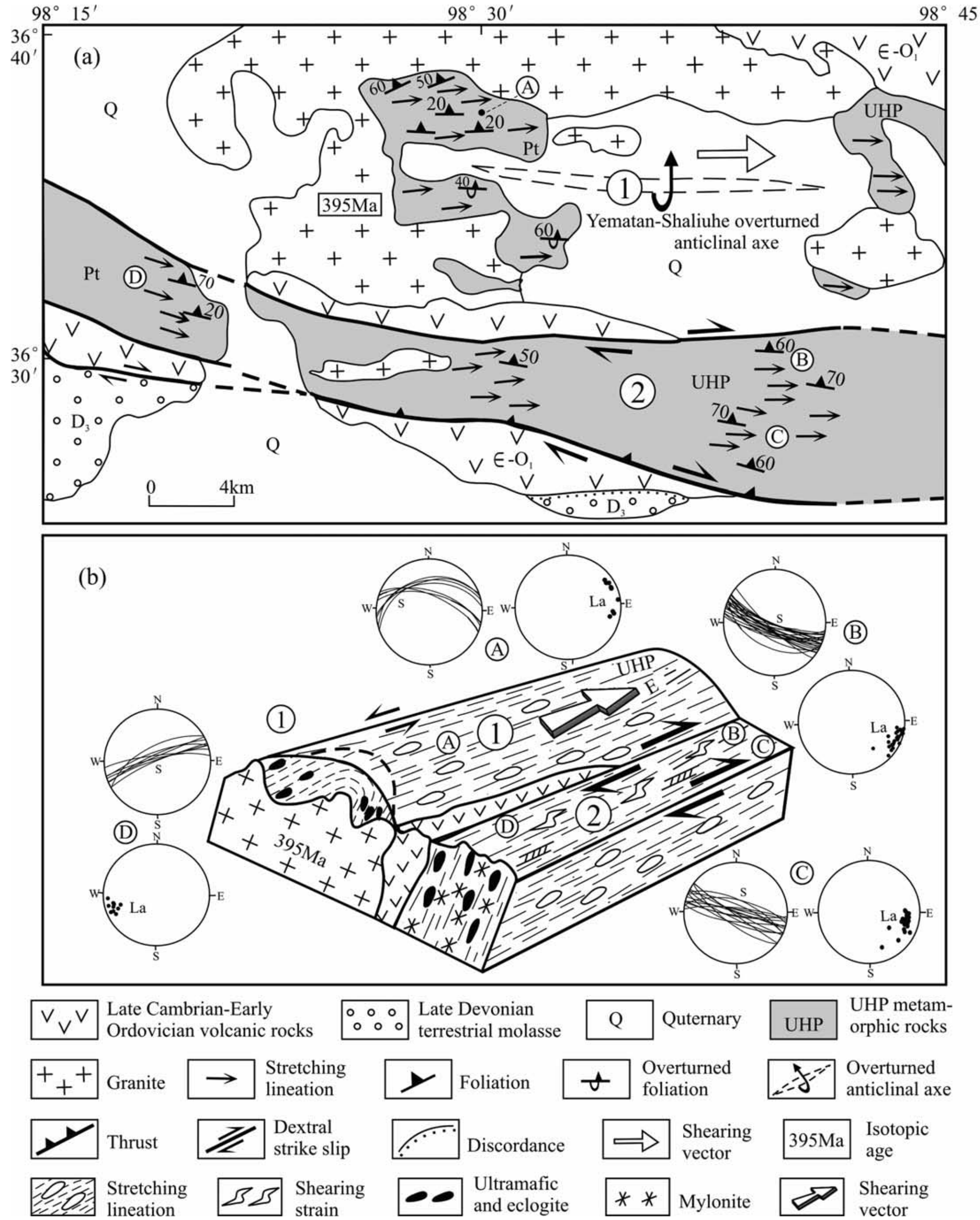

Fig. 2. Geological sketch map (a) and stereoscopic structural model (b) of Dulan UHP metamorphic zone (modified from the 1:200 000 Geological Map of the Dulan region, Qinghai Bureau of Geology and Mineral Resources). Diagrams at Fig. 2(b) border show projection of foliation (S) and stretching lineation (La) of the Dulan UHP metamorphic rocks: (Schimith circle, lower hemisphere projection): ① Yematan overturned anticline; ② Shaliuhe ductile dextral shear zone. Ⓐ: lower hemisphere projection of gently dipping foliation (S) and stretching lineation (La) in the middle part of the overturned anticlinal structure. Ⓑ, Ⓒ, Ⓓ: lower hemisphere projection of steep dipping foliation (S) and stretching lineation (La) in the southern limb of the overturned anticlinal structure.

conditions (500–650 °C and 1.5 GPa) at mid-crustal levels, but that as exhumation continued, the rocks moved into the greenschist facies, as indicated by the presence of hydrated minerals, such as muscovite, chlorite and actinolite. This later stage is estimated to have occurred at $T < 500$ °C and $P <$ 0.5 GPa in the upper crust (Song, 2001).

The exhumation structures of the Dulan UHPM terrain are composed of the Yematan overturned anticline at the north and the Shaliuhe dextral ductile transpression shear zone at the south.

3.1.1. Yematan overturned anticline

The foliation in the Dulan UHP zone generally strikes E–W and is folded into an overturned anticline. In the north limb of the anticline, the steeply northward-dipping foliation gradually flattens to the south, whereas along the southern limb the foliation is overturned and becomes the steeply north dipping (Fig. 2a,b).

The most striking structural feature of the Dulan UHP zone is the development of longitudinal, subhorizontal stretching lineations in the foliation, i.e. the stretching lineation is parallel to the strike of the zone and the orientation of the mountain belt. The lineation is manifested as stretching and breaking of eclogite bands, stretching and preferred orientation of kyanite grains, stretching of felsic minerals and development of boudins in granitic rocks and chert bands.

On the basis of measurements of foliation and stretching lineation in the overturned anticline, it shows that the stretching lineation has a constant attitude whether foliation varied. Where the foliation is steeply dipping, we found that the vertical stretching lineation is cut by a horizontal stretching lineation, which may represent the vector of movement at great depth during the early stages of exhumation.

Shear strain in the Dulan UHP zone is marked by σ- and δ-type porphyroclasts systems, S–C structures, asymmetric drag folds, domino structures and rotation of inclusions in garnet. In the gentle foliation of the top of the overturned anticline, the shear strain caused by the eastward slip of the hanging wall can be observed on the *XZ* plane perpendicular to the foliation (Fig. 3a). Steeply northward-dipping foliation zones are developed on both the north and south limbs of the overturned anticline and the shear strain is manifested by sinistral strike-slip movement on the north limb and dextral strike-slip movement on the south limb (Fig. 3c).

The sense of the shear strain was also determined by measuring the preferred orientation of 3 types of quartz in the subhorizontal foliation zone (Fig. 3b); stretched quartz, rectangular quartz in quartz bands and mylonitic quartz ($<$ 0.1 mm). Stretched quartz is observed on the *XZ* plane where the grains show marked wavy extinction and a subgrain structure. *X*:*Z* ratios may reach 10:1 or even 20:1 in these grains. The preferred orientation of these grains is formed by a basal-face fabric with the system $(0001)\langle a\rangle$, a rhombic-face fabric with the slip system $\{10\bar{1}0\}\langle a\rangle$ and a prismatic-face fabric with the slip system $\{10\bar{1}0\}\langle a\rangle$, reflecting the fabric patterns of quartz grains medium to medium-low temperature (600–350 °C). The rectangular quartz grains have length to width ratios on the *XZ* plane of 1.5:1–2:1. The patterns of preferred orientation are similar to those of stretched quartz showing medium- to medium-low-temperature fabrics of the slip systems (0001) $\langle a\rangle$, $\{10\bar{1}\bar{1}\}$ $\langle a\rangle$ and $\{10\bar{1}0\}$ $\langle a\rangle$ (Mainprice et al., 1986). The mylonitic quartz is characterized by very small grain size (<0.1 mm) but its preferred orientation is the same as that of stretched quartz and rectangular quartz.

Therefore, preferred orientation of quartz from the subhorizontal foliation shows also eastward slip of the hanging wall.

3.1.2. Shaliuhe dextral ductile transpression shear zone

The Shaliuhe ductile shear zone composed of granitic mylonite, mylonizated gneiss and intense shearing stain schiste is characterized by subvertical foliation and subhorizontal stretching lineation. A-type folds are well developed and the dextral strike-slip feature is shown on the *XZ* plan. In addition, southward thrusting is observed on the *YZ* plane, which indicating formation in a ductile transpression zone.

The preferred orientation of quartz in this ductile transpression shear zone is shown in Fig. 3b. The quartz grains show three types of preferred orientation, (0001) $\langle a\rangle$, $\{10\bar{1}\bar{1}\}$ $\langle a\rangle$ and $\{10\bar{1}0\}$ $\langle a\rangle$. These formed at medium-high to medium-low temperatures (400–650 °C) and reflect the dextral strike-slip motion of the hanging wall (Fig. 3d). The mineral assemblages in this foliation zone are Ab + Q + Bi + Mus, Mus + Bi + Mic + Pl + Q and Bi + An + Chl + Q, suggesting that amphibolite-facies to greenschist-facies metamorphism occurred during strike-slip shearing.

3.2. Structural features of the Da Qaidam segment

The NW–SE-trending Da Qaidam terrain is made up of the Xitieshan, Luliangshan and Iqe sub-terrains, each with a width of ∼3–4 km. The country rocks are composed of granitic gneiss and paragneiss of the Daken Dawan Group, and these contain nodules and lenses of eclogite, garnet peridotite and ophiolite lithologies. Although no coesite has been found in the Da Qaidam terrain, the *P*–*T* conditions of the eclogite and presence of coesite pseudomorphs provide evidence of UHP metamorphism (Zhang et al., 2000a,b).

The exhumed structures of the Xitieshan terrain are characterized by overtured anticline form caused by refolded foliation. The regional foliation generally strikes NNW. A NW–SE, subhorizontal stretching lineation marked by elongate sillimanite and feldspar grains, as well as felsic veins in the foliation, is similar to that in the Dulan terrain (Fig. 4).

Gneiss of the Xitieshan UHP terrain and Cambrian–Ordovician volcanic rocks have both been mylonitized and they exhibit southeast-oriented shear strain in the subhorizontal to gently dipping foliation at the top of the Xitieshan overturned anticline. The preferred orientations of mylonitic quartz and recrystallized rectangular quartz in the mylonitized gneiss are manifested by transformation from medium- to high-temperature ($>$600–450 °C) fabrics $\{10\bar{1}0\}$ $\langle c\rangle$ and $\{10\bar{1}0\}$ $\langle a\rangle$ to medium- to low-temperature (450–350 °C) fabrics $\{10\bar{1}\bar{1}\}$ $\langle a\rangle$ and (0001) $\langle a\rangle$ (Fig. 5a,b).

Gneiss of the Xitieshan UHP zone and Cambrian–Ordovician volcanic rocks have both been mylonitized in the southwest part of the Xitieshan anticline. The foliation of mylonite zone dips steeply to the north and the stretching lineations dip gently to the southeast with rake angles of 20–30°. The preferred orientations of mylonite quartz and recrystallizing rectangular quartz also show a transformation from medium-high to medium-low temperatures, and the shear strain indicates dextral strike-slip movement (Fig. 5c). The dextral strike-slip on the *XZ* plan and compression deformation on the *YZ* plan, which indicating dextral transpression features is similar to those of the Dulan UHPzone.

4. Timing of exhumation of the northern Qaidam UHP zone

In order to determine the exhumation age in the northern Qaidam UHP zone, we dated muscovite from the subhorizontal foliation in the Dulan overturned anticline and the subvertical mylonite foliation in the Xitieshan dextral transpression shear zone. We also dated granitic plutons intruded into the Dulan terrain.

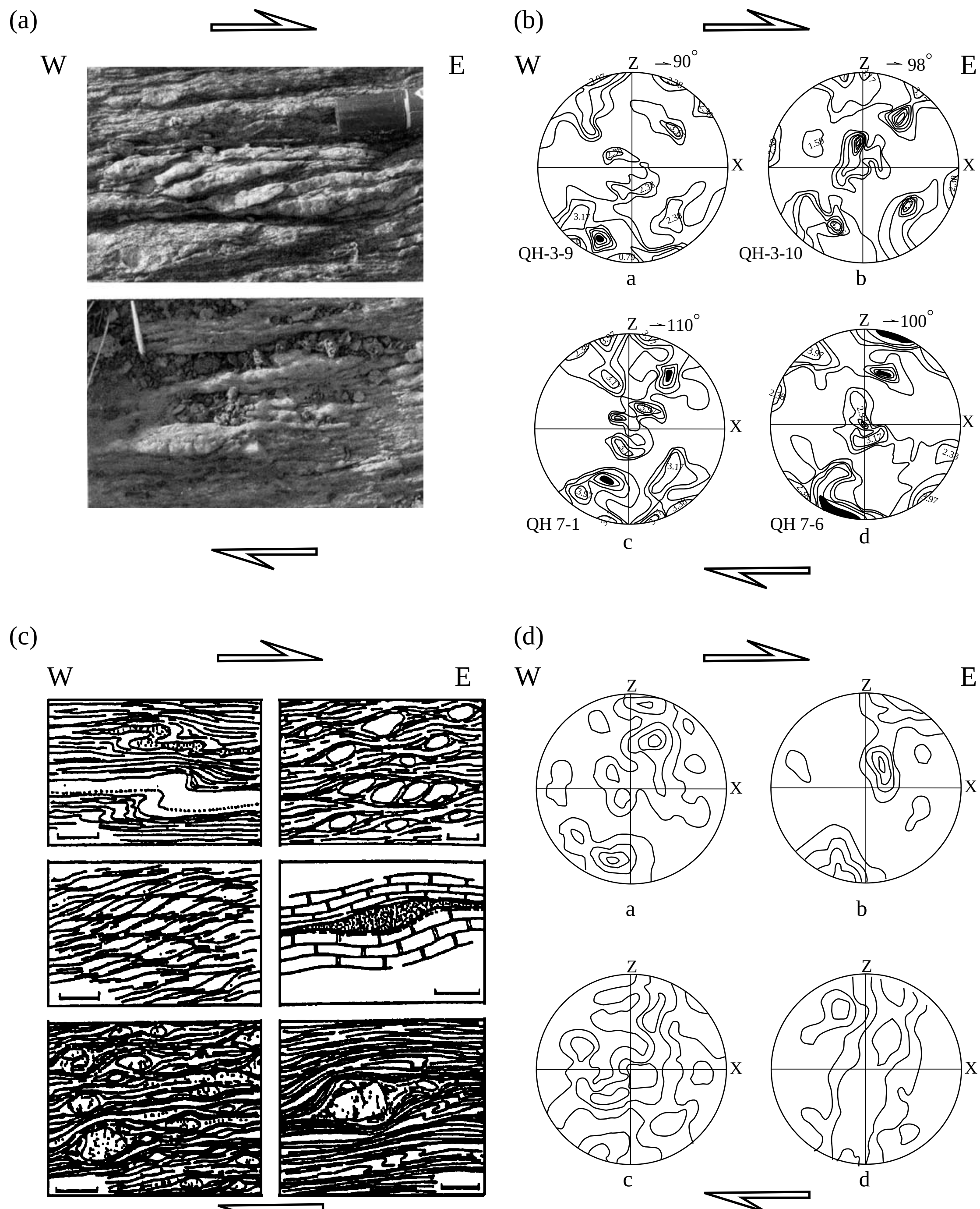

Fig. 3. Shearing strain and Letters Preferred Orientation of quartz of the Dulan UHP metamorphic rocks: (a) Photomicrograph on the gently dipping foliation of granitic gneiss at the middle part of the Yematan overturned anticline showing shearing sense eastward. (b) Lattice Preferred Orientations of quartz from granitic gneiss at the middle part of the Yematan overturned anticline showing shearing sense eastward. (Equal-area projection, lower hemisphere; 150 grains, Contours: 1-3-5-7-9-11%). (c) Shear strain of granitic mylonite in the Shaliuhe ductile dextral strike-slip shear zone. (d) Lattice Preferred Orientations of quartz from granitic mylonite of the Shaliuhe ductile dextral strike-slip shear zone (Equal-area projection, lower hemisphere; 150 grains, Contours: 1-3-5-7-9-11%).

In order to date the horizontal mylonite foliation we separated muscovite from coesite-bearing granitic gneiss. The rock dips 20°N and is mylonitized. The muscovite formed during mylonitization and shear deformation displays east-directed slip features. The sample 99-Y-117 was dated by the ^{39}Ar–^{40}Ar method at the Institute of Geology, Chinese Academy of Geological Sciences, Beijing. The sample yielded a very good plateau age of 401.5 ± 0.5 Ma (Fig. 6a). On the isochron diagram the ^{40}Ar–^{36}Ar intercept age is 209.2 ± 52.5 Ma and the isochron age is 406 ± 4.5 Ma, in good agreement with the plateau age (Table 1) (Fig. 6a,b). The muscovite closure temperature of 350 ± 50 °C for the K–Ar

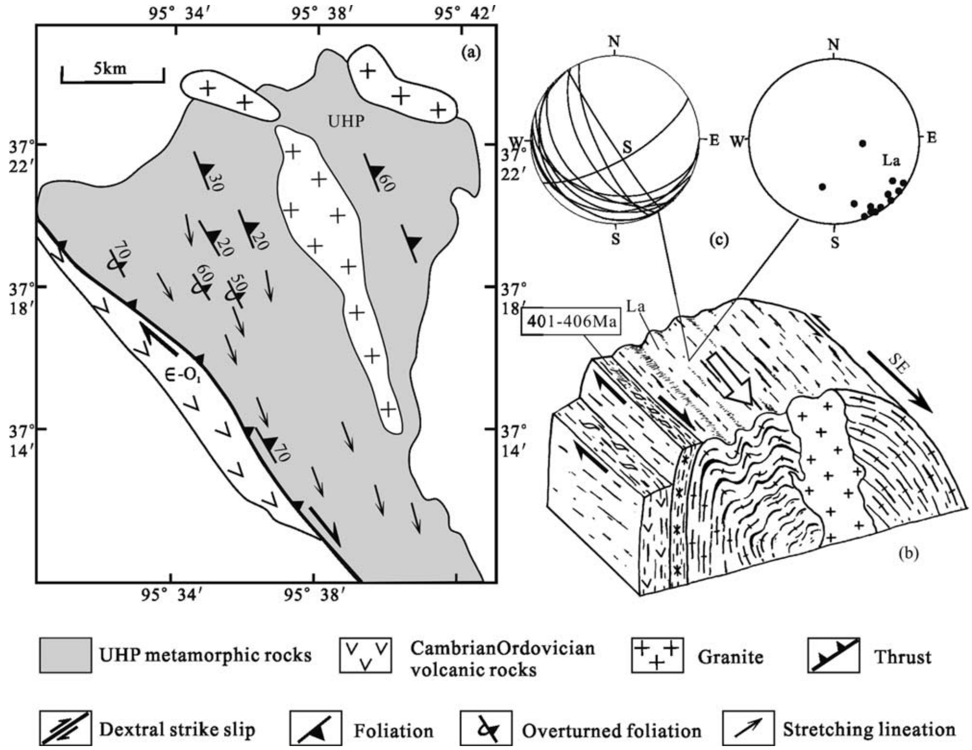

Fig. 4. Geological sketch map and stereoscopic structural model of the Xitieshan UHP metamorphic zone: (a) Geological sketch map of the Xitieshan UHP metamorphic zone. (b) Projection of gently dipping foliation (S) and stretching lineation (La) of the middle part of the Xitieshan overturned anticlinal structure. (c) Stereoscopic diagram of foliation (S) and stretching lineation (La) in the Xitieshan UHP metamorphic zone.

system reflects the time at which the UHP metamorphic terrain reached shallow depths of $\sim$10 km.

Muscovite from the mylonitized granitic gneiss sample ST18M of the south side of the Xitieshan zone was used to date the steeply dipping foliation. The mylonite foliation in this sample dips SE at 80° and the stretching lineation dips 145° at 30°. The plateau age obtained through 12 heating steps is 405.7 ± 0.9 Ma, and the ^{40}Ar–^{36}Ar intercept age on the isochron is 191.50 ± 13.80 Ma. The isochron age is 404.66 ± 4.3 Ma, similar to the plateau age (Table 2) (Fig. 6c,d).

The Yematan granite, intruded into the Dulan terrain, was dated at 397 ± 4 Ma using the zircon SHRIMP method sample (Wu et al., 2000). The Ar–Ar ages of mica cited above suggest that the gently-dipping and steeply-dipping or subvertical foliations in the zone formed at approximately the same time (400–406 Ma). This corresponds to the last stage of exhumation of the zone to shallow depths. The intrusion of the 397 Ma granite marks the end of exhumation of the UHP belt.

5. Mechanism of exhumation and model of evolution of the northern Qaidam UHP belt

5.1. Mechanism of exhumation of the northern Qaidam UHP belt

Exhumation of UHP metamorphic rocks from the deep mantle to the shallow crustal levels is a difficult problem that has not yet to be completely solved. A number of different models have been proposed, which fall into four categories: (1) erosion and buoyancy (Platt, 1993), (2) extension (Harrison, 1992), (3) vertical extrusion (Chemenda et al., 1995, 1996), and (4) extension of the upper crust and shortening of the lower crust (Anderson and Jamerit, 1990; Ballevere et al., 1990; Blake and Jayko, 1990).

The most striking exhumation structures in the north Qaidam UHP belt are the antiform formed by arching of the foliation, the longitudinal, subhorizontal ductile stretching lineation, and the shear strain displaying evidence of eastward slip and dextral transpression. Based on the isotopic age data (400–406 Ma), which show that the eastward slip and the dextral transpression structures are coeval, we suggest that exhumation involved a combination of vertical extrusion and transpression.

The vertical extrusion model suggests that during plate collision and deep subduction of continental crust, the UHP metamorphic slab ruptures and plate convergence causes the subducting slice to be exhumed by buoyancy forces. As a result of upward extrusion of soft material within rigid walls, the foliation in the upper part of the subducting slice is arched and a horizontal stretching lineation forms. This process is distinguished from simple horizontal compression in that the latter usually produces a vertical foliation and vertical stretching lineation.

The overturned anticline in the north Qaidam belt dips to the southeast and east and sinistral and dextral transpression structures occur on both limbs of the overturned anticline.

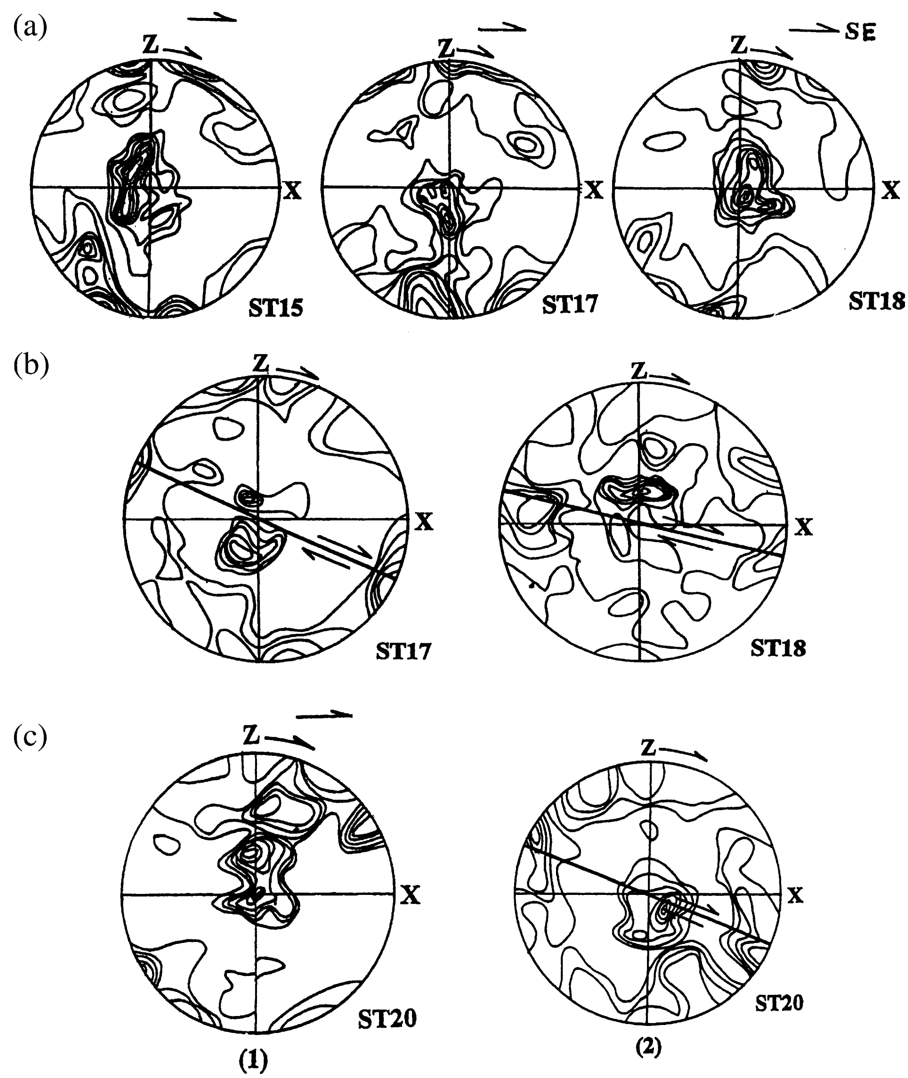

Fig. 5. Diagram showing the lattice preferred orientations of mylonite quartz in the Xitieshan UHP metamorphic zone. (a) Preferred orientation of rectangular recrystallized quartz in gentle-dipping mylonite foliation at the top of the Xitieshan overturned anticline (Equal-area projection; lower hemisphere; 150 grains. Contours: 1-3-5-7-9-11%). (b) Preferred orientation of mylonite quartz in gentle-dipping mylonite foliation at the top of the Xitieshan overturned anticline (Equal-area projection; lower hemisphere; 150 grains. Contours: 1-3-5-7-9-11%). (c) Preferred orientations of mylonite quartz (left) and recrystallized quartz (right) in the Xitieshan ductile dextral strike-slip shear zone (Equal-area projection; lower hemisphere; 150 grains. Contours: 1-3-5-7-9-11%).

The occurrence of the transpression structures at the south margin of the overturned anticline indicates that the driving force during exhumation was oblique convergence. Thus, the combination of oblique collision and subduction results in both 'vertical extrusion' and 'transpression'. We call this combined mechanism 'oblique extrusion'.

The Black Mountain axial zone of the Hercynian orogen in France is a metamorphosed dome composed of Precambrian gneiss, where the antiform due to foliation folding and longitudinal (nearly E–W-trending) stretching lineation are quite similar to the basic features of the northern Qaidam UHPM terrain (Fig. 7a). However, there are differences between the two belts. For example, the sense of shear strain on the east and west sides of the Black Mountain axial zone are just opposite to each other, i.e. the shear strain on the east side has an easterly sense, while that on the west side has a westerly sense, showing bidirectional shear. In contrast, the northern Qaidam UHP zone is not a domal anticline but an elongate body and the shear strain has an easterly sense, showing unidirectional shear. Matte et al. (1998) proposed that the Hercynian Black Mountain axial zone is not a metamorphic core complex but an anticlinal nappe resulting from N–S coaxial compression and longitudinal extension.

The mechanism of oblique extrusion for the northern Qaidam UHP belt is much more complex than that for the Black Mountain axial zone. Fig. 7b,c show a hypothetical three-dimensional model of 'oblique extrusion', showing that under the principal stress (Pp) produced by oblique plate convergence the UHP metamorphic slice is subjected to 'oblique extrusion' (Oe), which may be resolved into an eastward slip component (L), a vertical extrusion component

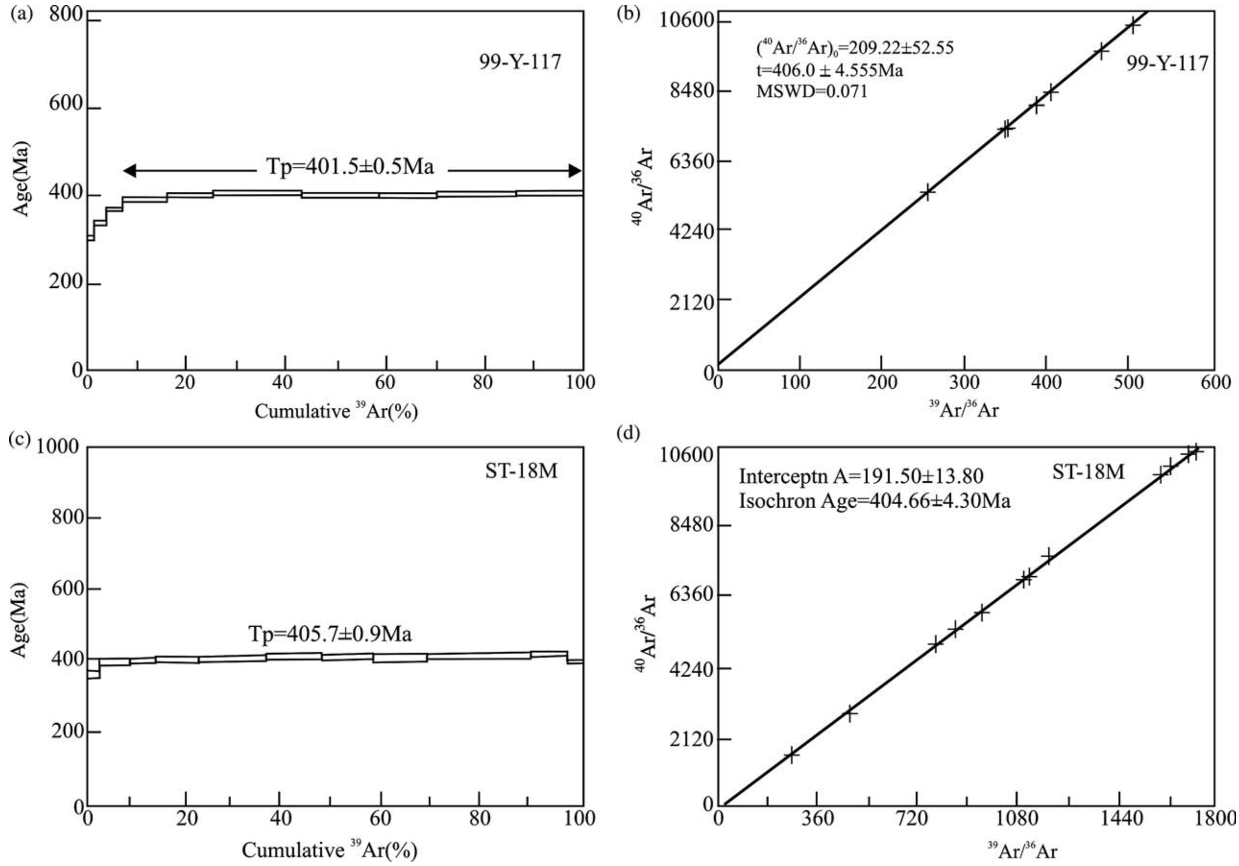

Fig. 6. Muscovite ^{39}Ar–^{40}Ar age diagram of the northern Qaidam UHP metamorphic rocks: (a) Muscovite ^{39}Ar–^{40}Ar plateau age diagram of garnet–muscovite gneiss in the northern Dulan UHP zone. (b) Muscovite ^{39}Ar–^{40}Ar isochron age diagram of garnet–muscovite gneiss in the northern Dulan UHP zone. (c) Muscovite ^{39}Ar–^{40}Ar plateau age diagram of mylonitized granitic gneiss in Xitieshan. (d) Muscovite ^{39}Ar–^{40}Ar isochron age diagram of mylonitized granitic gneiss in Xitieshan.

(Ve), a sinistral transpression component (Ss) and a dextral transpression component (Sd) (Fig. 7).

'Oblique extrusion' implicates the Qilian terrain was moved easterly opposite to the Qaidam terrain at about 400 Ma. It is not unique, but has its counterpart, the Alxe terrain was moved easterly opposite to the Qilian terrain at the same time (Xu et al., 1996). It is inferred that relative convergence between the Alxe and Qilian terrains was transformed from 'normal' to 'oblique' intracontinental subduction in late Caledonian.

5.2. Model for the formation and exhumation of the northern Qaidam UHP metamorphic belt

Paleomagnetism and global tectonic reconstruction studies (Hallam, 1992; Gradstein et al., 2004) suggested that the proto-Tethys Oceanic basin was present at the southern hemisphere between the Gondwanaland, Siberian plate, North America plate, and Baltic plate at ∼550 Ma, while the North China plate, South China plate and a series of other small terrains that constitute the northern Qinghai-Tibet composite terrain such as

Table 1
^{39}Ar–^{40}Ar data for muscovite from granitic gneiss on the horizontal mylonitic foliation

T (°C)	(^{40}Ar/^{39}Ar) m	(^{36}Ar/^{39}Ar) m	(^{37}Ar/^{39}Ar) m	^{39}Ar (×10^{-14}, mol)	^{39}Ar (%)	Age (Ma, 2σ)
400	22.9034	0.0276	0.0595	99.19	1.07	302.9±5.90
500	18.6586	0.0073	0.0745	236.08	3.61	336.0±4.70
600	19.9941	0.0063	0.0316	305.57	6.9	366.1±3.70
700	20.4162	0.0032	0.0185	839.40	15.96	390.1±3.90
800	20.8262	0.0028	0.0132	860.45	25.22	399.5±4.00
900	20.8751	0.0020	0.0102	1659.08	43.09	404.9±4.20
980	20.7693	0.0026	0.0081	835.61	52.09	399.9±4.00
1080	20.8971	0.0028	0.0146	679.56	59.42	400.8±4.40
1180	21.2045	0.0038	0.0242	1057.32	70.81	401.0±3.90
1280	20.8729	0.0025	0.0058	1492.20	86.88	402.3±4.10
1400	20.8007	0.0022	0.0411	1217.60	100	402.7±4.60

Table 2
^{39}Ar–^{40}Ar data for muscovite from granitic gneiss on the subvertical mylonitic foliation. Data step heating for ST-18M (Weight = 91.00 mg, J = 0.012948)

T (°C)	($^{40}Ar/^{39}Ar$) m	($^{36}Ar/^{39}Ar$) m	($^{37}Ar/^{39}Ar$) m	F	^{39}Ar ($\times 10^{-14}$, mol)	^{39}Ar (%)	Age (Ma)
500	36.66670	0.08890	0.52190	10.43660	9.00	0.09	228.70 ± 27.80
600	18.66670	0.00370	0.03130	17.58110	300.00	2.96	370.00 ± 4.70
700	79.48950	0.00110	0.03600	19.17720	666.00	9.34	400.10 ± 4.40
800	19.65430	0.00060	0.01530	19.48060	1562.00	24.31	405.80 ± 4.50
900	19.64010	0.00060	0.01830	19.45590	1306.00	36.82	405.30 ± 4.50
1000	19.95830	0.00080	0.02000	19.70900	1200.00	48.31	410.00 ± 4.50
1100	19.79770	0.00060	0.02310	19.60990	1038.00	58.26	408.20 ± 4.50
1200	19.64290	0.00090	0.02140	19.37610	1120.00	68.99	403.80 ± 4.50
1250	19.80580	0.00120	0.02790	19.45920	515.00	73.92	405.40 ± 4.50
1300	19.64910	0.00060	0.02800	19.47400	1710.00	90.30	405.60 ± 4.50
1350	19.94900	0.00130	0.06110	19.57260	784.00	97.82	407.50 ± 4.50
1400	19.21050	0.00220	0.42020	18.59380	228.00	100.00	389.20 ± 4.30

the Qilian–Altin terrain, the Qaidam terrain, the northern part of the eastern Kunlun terrain and the southern part of the eastern Kunlun terrain, were located probably between the proto-Tethys Oceanic basin and the Gondwanaland. These small terrains were separated by some seas such as the North Qilian Sea and the South Qilian Sea linked with the proto-Tethys Oceanic basin and formed a Caledonian chain of archipelago at late Devonian. During 500–440 Ma, the North Qilian Sea was subducted beneath the North China plate to 30–60 km deep and resulted in the northern Qilian HP metamorphic belt, while the South Qilian Sea and Qaidam continental crust were subducted beneath the Qilian terrain to 100 km deep and led to the formation of the northern Qaidam UHP metamorphic belt. Later arc–arc, arc–continent and continent–continent collisions at 410–400 Ma led to the juxtaposition and amalgamation of these terrains. Such collisional events were responsible for the intensive deformation of the accretional wedge above a subducted slab, formation of the Devonian molasses basins and large amounts of granitic intrusions in this region. Eventually, these terrains were welded with the North China plate to form the 'Early Paleozoic China collage'.

Above-mentioned studies provide the following geological records for the formation and exhumation of the northern Qaidam UHP metamorphic belt: (1) the proto-Tethys ocean basin formed at 515 Ma before; (2) the volcanic island arc by the subduction of the ocean basin and seas occurred at about 515– 485 Ma; (3) the north Qaidam UHP belt formed between 495 and 440 Ma; (4) the exhumation of the UHP terrain began at 470–460 Ma and completed at 400–406 Ma. The evolution history of the north Qaidam UHP terrain should be divided into the four stages (Fig. 8).

5.2.1. Subduction stage of the South Qilian Sea

The South Qilian Sea lying between the Qilian terrain and the Qaidam terrain was formed during Early-Middle Cambrian (about 515 Ma before). The South Qilian Sea was subducted northward beneath the Qilian terrain, the interaction of the subducted lithosphere and asthenosphere in the mantle wedge between the two terrains made the side of the obducted Qilian

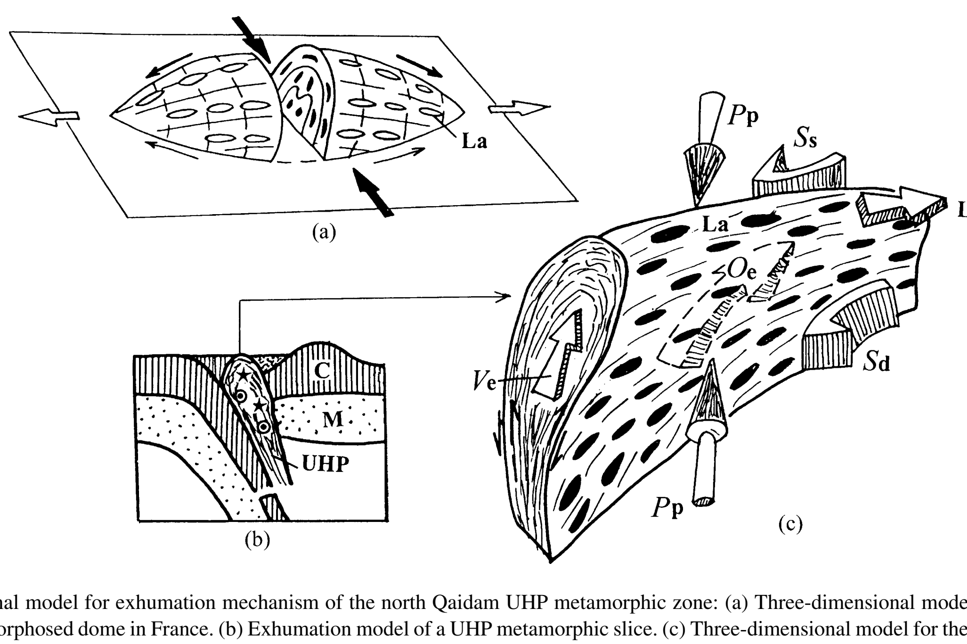

Fig. 7. Three-dimensional model for exhumation mechanism of the north Qaidam UHP metamorphic zone: (a) Three-dimensional model for the formation of the Black Mountain metamorphosed dome in France. (b) Exhumation model of a UHP metamorphic slice. (c) Three-dimensional model for the exhumation model of the north Qaidam UHP metamorphic terrane. Abbreviations: *P*p, direction of the principal stress of oblique collision and subduction; *O*e, oblique extrusion; L, eastward slip component; *V*e, vertical extrusion component; *S*s, sinistral transpression component; *S*d, dextral transpression component.

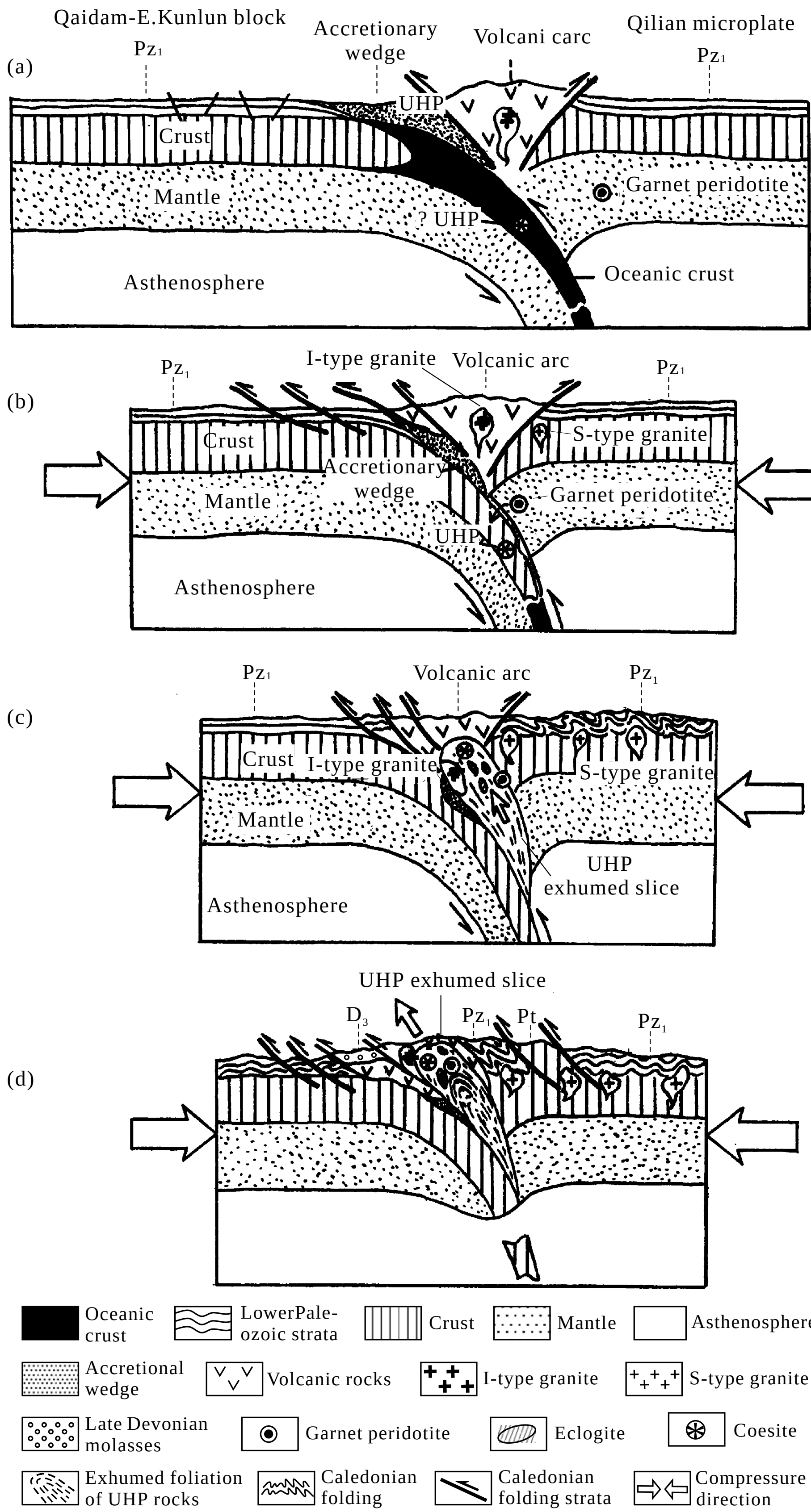

Fig. 8. Model of the formation and exhumation of the northern Qaidam UHP metamorphic zone: (a) Subduction of the South Qilian ocean basin (Late Cambrian–Early Ordovician). (b) Continentao deep subduction of the Qaidam-East Kunlun plate (495–440 Ma). (c) Exhumation of the Northern Qaidam UHP metamorphic slice (470–400 Ma). (d) Caledonides (after 400 Ma).

terrain to be weaked and spreaded, and the volcanic island arc was happened at 515–485 Ma.

5.2.2. Continental deep subduction stage of the Qaidam terrain

After the South Qilian Sea subduction, the continental crust including metamorphic basement of the Qaidam was carried deeply to be a great depth of more than 100 km and underwent UHP metamorphism between 495 and 440 Ma. Meanwhile the continued deep subduction, the exhumation of the subducted slice began at 470–460 Ma.

5.2.3. Exhumation stage of the north Qaidam UHP zone

The UHP zone was exhumed by a process of 'oblique extrusion' during transformation from 'normal' to 'oblique' intracontinental subduction between the Qilian and Qaidam terrains. Overall exhumation was occurred at 460–440 Ma and was completed by 406–400 Ma. Meanwhile, extensive retrograde metamorphism, reactivation of the metamorphic basement intensive folding of the Lower Paleozoic strata occurred and intruded of a large number of S-type collision granites.

5.2.4. End of Caledinian orogeny

The Qilian Mountains were built by Caledinian orogeny. Late Devonian molasses deposits indicating the end of Caledonian orogeny were cumulated in the foreland of the Caledonian folding belt by uplift and erosion at 372–354 Ma.

6. Summary and conclusions

The South Qilian Sea basin was subducted northward beneath the Qilian terrain beginning at 515–490 Ma, while a volcanic island arc, I-type granites and a fore-arc accretionary wedge (pyroclastic rocks + marble) formed along the southern margin of the Qilian terrain. Later (495–440 Ma), deep subduction (> 100 km) of continental crustal rocks (including 900–1100 Ma metamorphosed basement) of the Qaidam terrain produced the north Qaidam UHPM zone. The initial stage of exhumation for the UHPM slice began at 470–440 Ma. The overall exhumation occurred at 440–410 Ma. The final exhumation happened at 400–406 Ma accompanied by retrograde metamorphism and intrusion of voluminous S-type collision granites. Deep subduction of continental crust slice and exhumation of the UHPM slice were happened alternately during 470–440 Ma.

The entire UHPM slice was exhumed by 'oblique extrusion' was transformed from 'normal' to 'oblique' intracontinental subduction in late Caledonian and underwent retrograde metamorphism. Driven by buoyancy forces, the UHP block was indented into the volcanic island-arc and fore-arc belt and was juxtaposed against the island arc.

Acknowledgements

This research was supported by the key project 'Material Composition and Orogenic Process of the Qilian Orogenic Belt' of the National Natural Science Foundation of China (grant G 1998040800), the key fundamental research project of the Ministry of Land and Resources and Sino-French cooperative project 'Tectonic Evolution and Lithosphere Shearing of the Qilian–Altun Mountains' (1966–2000) and the China Geological Survey project 'Tectonic Framework and Mineralization in the Qilian Mountains'. The authors are grateful to Prof. P. Lobinson of Canada and Prof. M. Mattauer of France for their helpful suggestions on the exhumation mechanism outlined in this paper and Zhang Xiaowei, Tang Zhemin, Liang Fenghua and Wu Guixiang for their assistance in the completion of the manuscript.

References

Anderson, T.B., Jamerit, B., 1990. Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord region of Western Norway. Tectonics 9, 1097–1111.

Ballevere, M., Lagabrille, Y., Merlr, O., 1990. Tertiary ductile normal faulting as a consequence of lithospheric stacking in the Western Alpes. Memoirs of the Geological Society of France 156, 227–236.

Blake, M.C.J., Jayko, A.S., 1990. Uplift of very high pressure rocks in the western Alps: evidence for structural attenuation along low-angle fault. Memoirs of the Geological Society of France 156, 237–246.

Bureau of Geology and Mineral Resources of the Qinghai Province, 1991, 1991, 1991.Anon., 1991. Regional Geology of Qinghai Province. Geological Publishing House, Beijing pp. 1–662.

Chemenda, A.I., Mattauer, M., Malavielle, J., Bokun, A.N., 1995. A mechanism for syn-collisional rock exhumation and associated normal faulting: Results from physical modelling. Earth and Planetary Science Letters 132, 225–232.

Chemenda, A.I., Mattauer, M., Bokun, A.N., 1996. Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: New modeling and field data from Oman. Earth and Planetary Science Letters 143, 173–182.

Coleman, R.G., Wang, X., 1995. Ultrahigh-Pressure Metamorphism. Cambridge University Press.

Cui, J.W., Tang, Z.M., Deng, J.F., Yue, Y.J., Meng, L.S., Yu, Q.F., 1996. Altun Fault System. Geological Publishing House, Beijing p. 249.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Agterberg, F.P., Bleeker, W., Cooper, R.A., Davydov, V., Gibbard, P., Hinnov, L., House, M.R., Lourens, L., Luterbacher, H.-P., McArthur, J., Melchin, M.J., Robb, L.J., Shergold, J., Villeneuve, M., Wardlaw, B.R., Ali, J., Brinkhuis, H., Hilgen, F.J., Hooker, J., Howarth, R.J., Knoll, A.H., Laskar, J., Monechi, S., Plumb, K.A., Powell, J., Raffi, I., Rohl, U., Sanfilippo, A., Schmitz, B., Shackleton, N.J., Shields, G.A., Strauss, H., Van Dam, J., Van Kolfschoten, T., Veizer, J., Wilson, D., 2004. A geologic time scale 2004. Columbia University Press, New York.

Hallam, A., 1992. Phenerozoic Sea-level Changes. Columbia University Press, New York p. 266.

Harrison, C.G.A., 1992. Rates of continental erosion and mountain buiding, Proceedings of the 21th IGC. Kyoto, Japan p. 2.

Juang, W.S., Sun, M.Z., 2002. Isotopic and geochemistry evidence of granitoids of reactivation of basement of the Qilian Fold Belt, The Third (2002) Cross-Strait Conference on Geology of Qilian Mountains and Adjacent Area- Evolution of the Central Orogenic Belt, pp. 120–122Liou, J.G., Zhang, R.Y., Ernst, W.G., 1994. An introduction to ultrahigh-pressure metamorphism. The Island Arc 3, 1–24.

Kretz, R., 1983. Symbols for rock-forming minerals. American Mineralogist 68, 277–279.

Li, H.K., Lu, S.N., Zhao, F.Q., 1999. Chorology of upper-proterozoic main strata events in North Qaidam. Geochemica 13, 224–225.

Liou, J.G., Zhang, R.Y., Ernst, W.G., 1994. An introduction to ultrahigh-pressure metamorphism. The Island Arc 3, 1–24.

Liu, L., Che, Z.C., Luo, J.H., Wang, Y., Gao, Z., 1996. Determination of ecologite in the west segment of Altun mountains and its geological significance. Chinese Science Bulletin 41, 1458–1488.

Mainprice, D., Boucher, T.L., Blumenfeld, P., Tubia, J.M., 1986. Dominant < c > slip in naturally deformed quartz: implications for dramatic plastic softening at high temperature. Geology 14, 819–822.

Matte, Ph., Lancelot, J., Mattauer, M., 1998. La Zone axiale hercynienne de la Montagne Noiren'est par un 'metamorphic core complex' extensive mais un anticlinal post nappe a coeur anatectique. Geodinamica Acta, Paris 11, 13–22.

Platt, J.P., 1993. Exhumation of high pressure rocks: A review of concepts and processes. Terra Nova 5, 119–133.

Shi, R.D., Yang, J.S., Wu, C.L., Tsuyoshi, I., Takakumi, H., 2004. Island Arc volcanic Rocks in the North Qaidam UHP metamorphic Belt. Acta Geologica Sinica 78, 52–64.

Song, S.G., 2001. Petrology, mineralogy and metamorphic evolution of the Dulan UHP terrane in the northern Qaidam, NW China, and its tectonic implications. PHD dissertation, Cags: 1–96.

Song, S.G., Zhang, L.F., Niu, Y., Song, B., Liu, D.Y., 2004. Early Paleozoic plate-tectonic evolution and deep continental subduction on the northern margin of the Qinghai-Tibet Plateau. Geological Bulletin of China 23, 918–925.

Wan, Y.S., Yang, J.S., Xu, Z.Q., Wu, C.L., 2000. Geochemical characteristics of the Maxianshan complex and Xinglongshan group in the eastern segment of the Qilian orogenic belt. Journal of the Geological Society of China (Taiwan) 43, 52–68.

Wu, C.L., Yang, J.S., Li, H.B., Shi, R.D., 2000. Petrogenesis of the granitoides from Lenghu, northern margin of Qaidam basin, NW China. Journal of the Geological Society of China (Taiwan) 43, 107–124.

Wu, C.L., Yang, J.S., Ireland, T., Wooden, J., Li, H.B., Wan, Y.S., 2001. The SHRIMP age of zircon for Aulaoshan granite in the south Qilian, and its significance. Acta petrological sinica 17, 215–221.

Wu, H.Q., Feng, Y.M., Huo, Y.G., Song, S.G., 1993. Metamorphism and deformation of blueschist belts and their tectonic implications, North Qilian Mountain, China. Journal of Metamorphic Geology 11, 523–536.

Xia, L.Q., Xia, Z.C., 1991. Marine volcanic rocks in Qilian–Qinling Mountains. Geological publishing house of China university of Geosciences, Wuhan pp. 59–105.

Xia, L.Q., Xia, Z.C., Ren, Y.X., Zuo, G.C., Qiu, J.X., 1998. Volcanism and Mineralization in Qilian Mountains and Its Adjacent Area. Geological publishing house, Beijing p. 215.

Xiao, X.C., Cheng, G.M., Zhu, Z.Z., 1978. The geologic-tectonic significance of ophiolite in Qilian Mountains. Acta Geologica sinica 52, 195–287.

Xu, Z.Q., Xu, H.F., Zhang, J.X., 1994. Zoulangnanshan Caledonian subduction complex in north Qilian Mountains and its dynamics. Acta Geologica Sinica 68, 1–5.

Xu, Z.Q., Cui, J.W., Zhang, J.X., 1996. Deformation Dynamics of Continental Mountain Chains. Metallurgical industrial publishing house, Beijing pp. 1–246.

Xu, Z.Q., Yang, J.S., Zhang, J.X., Jian, M., Li, H.B., Cui, J.W., 1999. A comparison between the tectonic units on the two sides of the Altyn Tagh sinistral strike-slip fault and the mechanism of lithospheric shearing. Acta Geologica Sinica 73, 193–205.

Xu, Z.Q., Zhang, J.X., Li, H.B., 2000. Architecture and orogeny of the northern Qilian orogenic belt, NW China. Journal of the Geological Society of China (Taiwan) 43 (1), 125–141.

Xu, Z.Q., Li, H.B., Chen, W., Wu, C.L., Yang, J.S., Jin, X.C., Chen, F.Y., 2002. Acta Geologica Sinica 76 (2), 183–193.

Yang, J.S., Xu, Z.Q., Li, H.B., Wu, C.L., Cui, J.W., Zhang, J.X., Chen, W., 1998. Discovery of eclogite in the north Qaidam. Chinese Science Bulletin 43, 1544–1549.

Yang, J.S., Xu, Z.Q., Li, H.B., Wu, C.L., 2000. A Caledonian convergent border along the Qilian terrain, NW China: evidence from eclogite, garnet–peridotite, ophiolite, and S-type granite. Journal of the Geological Society of China 43, 142–160.

Yang, J.S., Song, S.G., Xu, Z.Q., Wu, C.L., Shi, R.D., Zhang, J.X., Li, H.B., Wan, Y.S., Liu, Y., Qiu, H.J., Liu, F.L., 2001. Discovery of coesite in the north Qaidam early Paleozoic ultralhigh–high pressure (UHP–HP) metamorphic belt, NW China. Acta Geologica Sinica 75, 175–179.

Yang, J.S., Xu, Z.Q., Zhang, J.X., Song, S.G., Wu, C.L., Shi, R.D., Li, H.B., Maurice, B., 2002. Early Paleozoic North Qaidam UHP metamorphic belt on the northeastern Tibetan plateau and a paired subduction model. Terra Nova 14, 397–404.

Yuan, B.G., Wang, M.G., Li, H.M., Hao, G.J., Xin, H.T., Zhang, B.H., Wang, Q.H., Tian, Q., 2002. The U–Pb age of Zircon from gabbro of the Luiliangshan area at the northern margin of Qaidam basin and its significance. Researching Progresses of Precambrian 25, 36–40.

Zhang, J.X., Xu, Z.Q., 1995. Caledonian subduction accretionary complex/-volcanic arc belt in middle sector of the north Qilian mountains and its deformational features. Acta Geoscientia Sinica, 154–163.

Zhang, X.T., Lu, H.Q., Cheng, Z.X., 1999. Discovery and preliminary study of high pressure metamorphic rock-eclogite facies in Shaliuhe area, north Qaidam. Qinghai geology 2, 1–12.

Zhang, J.X., Zhang, Z.M., Xu, Z.Q., Yang, J.S., Cui, J.W., 2001. Petrology and geochrology of eclogite from the western segment of the Altyn Tagh, northwestern China. Lithos 56, 187–206.

Zhang, J.X., Yang, J.S., Xu, Z.Q., Zhang, Z.M., Chen, W., Li, H.B., 2000a. Peak and retrograde age of eclogites at the northern margin of Qaidam basin, northwestern China: evidences from U–Pb and Ar–Ar dates. Geochemica 29, 217–222.

Zhang, J.X., Yang, J.S., Xu, Z.Q., Zhang, Z.M., Li, H.B., Chen, W., 2000b. U–Pb and Ar–Ar ages of ecologites from the northern margin of the Qaidam basin, northwestern China. Journal of the Geological Society of China (Taiwan) 43, 161–169.