2003-2006

China National Report on Volcanology and Chemistry of the Earth's Interior

For

The 24rd General Assembly of IUGG

Perugia, Italy, 2-13 July, 2007

By Chinese National Committee for

The International Union of Geodesy and Geophysics

Beijing, China

June, 2007

PREFACE

Over the past four years (2002-2006), considerable progress has been made by Chinese geologists in the field of volcanology and chemistry of the earth's interior. This IAVCEI national report highlights some of major achievements on the volcanism and its environmental impact, lithospheric structure and evolution. *Sun et al.* summarize the main characteristics of Cenozoic phreatomagmatic eruptions and discuss the mechanism and dynamics of eruption. *Guo et al.* review recent advances on the effects of intermediate-acidic explosive volcanism on paleo-environment changes and mass mortalities of vertebrate. In particular, they discussed the environmental effect of the Mt. Changbai volcanic eruption around 1000 years ago and Mesozoic intermediate-acidic volcanism in western Liaoning province, northeastern China. On the basis of studies on xenolith and terrane peridotites from eastern North China, *Zheng* describes the transitions of the complex cratonic mantle to the simple 'oceanic' lithospheric one, which involves lateral spreading (extension), melt-rock interaction, asthenospheric erosion and mantle replacement. *Sui* reviews recent works on the Hannuoba xenoliths and argues that magma underplating is one of the essential mechanisms operative during the Mesozoic geodynamic evolution of the North China Craton. Adakite is a peculiar rock type that has attracted much attention of the Chinese petrologists. *Wang et al.* distinguish three different types of adakites in terms of chemical composition, tectonic setting and associated mineralisation. The spatial and temporal distribution of the postcollisional ultrapotassic rocks and related potassic rock in the Lhasa Block leaded *Zhao and Mo* to suggest that break-off or delamination of the subducted oceanic/continental materials may have played an essential role in the genesis of these rocks in Tibet. Finally, *Xu* reports the major scientific achievements of the first IAVCEI meeting in China.

I would like to thank all the contributors for their enthusiastic involvement and cooperation to bring out this report in time. I also want to express my sincere thanks to Prof. Qicheng Fan for his suggestion and advice and to the Chinese Committee of IUGG for the guidance and support during the preparation of this report. This work benefited the supports from the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences and National Science Foundation of China

(40673038; 49925308).

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May 18, 2007

NEW PROGRESS ON VOLCANIC PHREATOMAGMATIC ERUPTION STUDY IN CHINA

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Abstract As an essential and important type of volcanic eruption on earth, phreatomagmatic eruption is characterized by groundwater-related explosive eruption, subsequent base surge deposit and maar lake. Base surge deposits and maar lakes are familiar all over the world, and are also in the Northeast China and the Southern China. The study of phreatomagmatic eruption dates back to 1921, and in the following 80 years, many works have been done on it. Based on previous works and take the large quantities of phreatomagmatic maars and base surges located in Quaternary volcanic area around Beibu bay in southern China for example, we summarize the study progress in China and profoundly discuss the geological features of base surge deposits, basic constraints of forming phreatomagmatic eruptions, mechanism and dynamics, and their transportation, etc. We also list the difficulties to be solved and discover the characteristics of these volcanic activities.

Key words phreatomagmatic eruption, maar, base surge, dynamic mechanism

I. INTRODUCTION

Phreatomagmatic eruption, which is different from familiar flooding and explosive eruption, is a special type of volcanic activity and meantime a common eruption type.

In China, there are a lot of maars and base surges originated from phreatomagmatic eruption, most of which are distributed in Quaternary volcanic region in Longgang，Northeast China, Northern Bay of South Leizhou Peninsula (Liu *et al*., 2000)，Weizhou Island (Fan *et al*., 2006) and North Hainan Island (Sun *et al.*, 2005). In Longgang volcanic group， there are eight maars filled with water, locally called‘Dragon Bay’. The craters and rims are mainly composed of base surges (Liu *et al*., 1997). Besides, there are some maars without water, called ‘Dry Dragon Bay’. In south

China coast areas, Leizhou Penisula and North Hainan Island, there exists a lot of maars and base surges (Liu *et al*., 2000; Huang *et al*., 1993; Sun *et al*., 2003). The Weizhou Island and Xieyang Island of Guangxi Province are the typical volcanic islands formed from magmatic and phreatomagmatic eruptions alternately. In these areas, the base surges and volcanic detrital rocks are overlapped each other, and almost cover the whole islands. Maars and base surges are also distributed in Jingbo Lake, Heilongjiang Province, and Aershan, Inner Mongolia.

In view of eruption mechanism, the so-called phreatomagmatic eruption includes the following processes: in a volcanic activity, the ascending hot magmas meet water (refers to the water in the aquiferous sediments), they explode immediately, produce large impact force upwards, make the overlain strata bend, crack, collapse and so on, at last the different-sized near rounded maars and base surges are formed. In these processes, the magma and the water co-play the important role. For these volcanic activities, many scholars in the world have described the field characteristics and studied its genesis mechanism through many methods such as volcanic geology, petrology, sedimentlogy, physical-volcanology and numerical simulation (Liu *et al*., 2000; Sohn *et al*., 1993; Liu *et al*., 1997; Sun *et al*., 2003; Lorenz, 1986; Wohletz, 2002; Du *et al*., 1989; Dellino *et al*., 2000; Sun *et al*., 2005). So lots of data about this type of volcanic activities have been accumulated.

II. GEOLOGICAL CHARACTERISTICS OF MAARS AND BASE SURGES

During the phreatomagmatic eruption, the base surges are diffusing outwards from the center eruptive column. Particularly in the contact region of the ascending magma column and the water within the sediments, the diffusing phenomenon is much more obvious (Liu *et al*., 1997; Sun *et al*., 2003). This type of base surges is derived from the eruptive column passing through laterally, which includes lots of vapor, volcanic ash and lapillus. The condensed vapor, as a part of the base surges, is mixed with the volcanic debris within the base surges, supports and dilutes them (Liu *et al*., 1997).

Maars and base surges are the typical products of phreatomagmatic eruptions. All the maars have a common nature of round or near round shape, however, some are filled with water (Longgang Dragon Bay in Jilin province, and Huguangyan of Leizhou Peninsula in Guangdong Province), the others are not (most of them in North Hainan Island). The sizes and preservation degrees of the maars are different. For example, during the field investigation in North Hainan Island, some are preserved very well for observation; the others are destroyed seriously and could be observed only by the trace, but their original appearance can be roughly reconstructed by field tracing. The sizes of maars differs obviously: the large ones have the diameter of more than 2000m, while the small ones have the diameter of less than 100m (Sun *et al*., 2005).

Belonging to turbulent flow, the base surge is also called volcanic debris density flow. It will become the sedimentary gravity flow when the energy decreases. The grains levelling to volcanic ash and some fine-grained accretion volcanic lapillus mix within the turbulent flow and are transported by suspending form. At the same time, the transportation depends on the equilibrium of the shearing stress and sedimentary rate. Finally, the grains are transported by the tractive current as base load form (Dellino *et al*., 2000). The final forming base surges have such structures as large-scale low angle platy-bedding, cross-bedding, wavy-bedding, and semi-sand dune. The type of structure has the obvious laminar texture, the top of which migrates to the lower region of the base surge. The accumulation sequences of this type of base surge are relatively complex with multi-cyclicity, whose rhythm characteristics are apparent (Xu *et al*., 2005). Within some distance from eruptive center, the indicating material—accretion volcanic lapilli are very common. The outer shape of the accretion volcanic lapillus is semi-rounded, diameter of which is up to 2~5mm. It has the developed layer and circle structures containing homocentric pellets. The layer and circle could be peeled off one by one. The structure is formed by the following processes: the fine debris from the exploding vapor is carried by the base surge and moves away from the crater; during the period, the surface of the debris coheres some fine volcanic ash and dust, and the mixture rolls ceaselessly; so the rounded layer and circle are formed (Sun *et al*., 2003). The base surge has another important feature of climbing-bedding. The base surge along the inner wall ascends outwards, which toward-flowing face has the steep gradient, but anti-flowing face has the flat gradient. There is an obvious transition end between them. Generally speaking, if the base surge ascends along the terrain barrier to some high, the gradient will somehow become flat. This is the typical feature of the phreatomagmatic eruption, which help us ensure center eruption positions of some poor-preserved maars. At the same time, it will be the important mark to differ from the common sediments under water.

It should be pointed out that the magma eruption and phreatomagmatic eruption occur alternately in many Quaternary basaltic volcanic region of China. During the field investigation, we usually find that a relatively intact profile is composed of base surges, fine volcanic ash, breccias, conglomerates and bombs, which show the complexity of the volcanic activity.

III. Dynamic Mechanism of Phreatomagmatic Eruption

When the phreatomagma eruption occurs, the magma and aquiferous sediments interplay each other and result in hydrous-thermo exploding, which bursts the overlain strata to form the maars and base surges. So the exploding impact force and stress state of the overlain strata become the basical parameters to study the dynamic mechanism of the phreatomagatic eruption. For many maars derived from the phreatomagatic eruption in North Hainan, we adopt the basic principle of elastic mechanics to establish the simple eruption model (Sun *et al*., 2005).

Because the maars are near rounded, the overlain strata burst by the phreatomagatic eruption may be considered to be rounded elastic sheet. The principle of the elastic sheet can be adopted to trace the relationship between destruction & collapse and exploding impact force. We set the following hypothesis to calculate: a—the radius of a maar, I—upward exploding impact force in the condition of $r \le r_0$, $r_0 < a$, where I is considered to be equal load, and r_0 is the radius of the contract surface of the magma and water. The exploding impact force (I) must be large enough to burst the overlain strata and form the maars. According to the condition we can deduce the mathematical expression of exploding impact force (I) and stress state of the overlain strata. After calculating mathematical expression of the stress, we can get the max stress. According to the max stress, we know which part of the overlain strata endures the max stress, where the strata will be destructed to collapse and form the maars observed in the field.

The calculation is according to the rounded sheet axis-symmetry theory. Establishing the model aims to ensure the impact force (I) and the stress state of all the points in the overlain strata. Obviously, the region in the condition of $0 \le r \le r_0$ must be considered first, as well as the weight of the overlain strata. The impact force (I) is calculated as following (Sun *et al*., 2005):

$$I = \frac{16Eh^3 w_1}{3(1-\mu^2) r_0^2 r^2 \left[\frac{r^2}{r_0^2} + \frac{2(1-\mu)}{1+\mu} \bullet \frac{r_0^2}{a^2} - 8\ln\frac{a}{r_0} - \frac{8}{1+\mu} \right]} + \rho g \pi a^2 h \qquad (1)$$

Where, I —impact force; E —Young modulus，h —the thickness of the overlain aquiferous sediments; μ —Poisson ratio， a —radius of the maar.

However, there will be no impact force in the region with the condition of $r_0 \le r \le a$, where the overlain strata will be only curled.

By the equation (1), some conclusions can be drawn as follows: the larger the radius of maar is, the larger the explosive wallop is needed to form a maar; provided that the radius of maar and depth of explosive point are limited, then the larger the area of contact surface between magma and groundwater is, the stronger the explosive energy is. If the explosive energy and area of explosive point are restricted, the larger the radius of maar is, the greater the depth of explosive point can be inferred. When the explosive energy and radius of maar are fixed, the depth of explosive point decreases with increasing of the area of contact surface between magma and groundwater.

The equation of stress state on any point in the overlain strata is:

$$\begin{cases} (\sigma_r)_{\max} = \frac{3Ir_0^2}{8h^2} \left[4(1+\mu)\ln\frac{a}{r_0} + 4 - (1-\mu)\frac{r_0^2}{a^2} - (3+\mu)\frac{r^2}{r_0^2} \right] \\ (\sigma_\theta)_{\max} = \frac{3Ir_0^2}{8h^2} \left[4(1+\mu)\ln\frac{a}{r_0} + 4 - (1-\mu)\frac{r_0^2}{a^2} - (1+3\mu)\frac{r^2}{r_0^2} \right] \end{cases} \qquad (2)$$

To work out equation (2), we needs to compile a small-scale VB program. The user needs only to input such parameters as thickness of overlain strata, radius of maar, radius of contract surface of the magma and water, impact force into a textbox, then click the “button of calculate” to work out the max stress on every point in the overlain strata.

IV. TRANSPORT PROCESS OF BASE-SURGE CURRENT

Base-surge current is a turbulent, dilute gravity flow, which is formed by volcanic pyroclastic. This kind of flow is dilute currents which have a Newtonian behavior and their characteristic features could be modeled by sedimentary dynamics (Sohn, 1997). The motions of particles in base surge are dominated by turbulence and the average velocity can be approximately calculated by equation (3) (Middleton *et al*., 1984):

$$\frac{u}{u^*} = 2.5\ln\frac{y}{k_s} + 8.5 \qquad (3)$$

where u is the velocity, u^* is the shear velocity, y is the height of the current and k_s is the substrate irregularity. Furthermore, we can calculate the shear velocity of the surge with the velocity of particles in the deposit. The settling velocity can be calculated using the equation (4) (Le Roux, 1992):

$$w = \sqrt{\frac{4g\phi(\rho_s - \rho_f)}{3C_d\rho_f}} \qquad (4)$$

where g is the gravity acceleration, ϕ is clast size and C_d = 0.5 is the coefficient of drag, ρ_s is the particles density, ρ_f is the density of the fluid component, which is given by equation (5) (Lajoie *et al*., 1989):

$$\rho_f = (1 - C)\rho_a + C\rho_s \qquad (5)$$

where ρ_a is the free fluid and C is particle concentration. Now, all of parameters of equations can be acquired. Using equation (4) and equation (5), we can calculate the shear velocity u^*, then take u^* into the equation (3), the relationship between the height of current and the transport velocity can be found.

A very important factor in model is the grain size of the suspension population in the surge. We try to inverse the granularity of particles that suspend within the base surge by means of equation (6) (Middleton, 1976):

$$\phi_i = \phi_{i0}\left(\frac{y_0}{1 - y_0}\right)^{P_n}\int_{y_0}^{1}\left(\frac{1 - y}{y}\right)^{P_n} dy \qquad (6)$$

where ϕ_i is the proportion of the *i*th grain size class in turbulent suspension in the deposit, y_0

is the reference level at which the grain size is known, y is the dimensionless height of the current, P_n is the particle Rouse number, which is obtained by $P_n = w / ku^*$ (Dellino *et al.*, 2000). The Rouse number allows the calculation of the concentration profile as a function of height of the surge by means of equation (7) (Valentine, 1987):

$$S = S_0 \left(\frac{y_0}{1 - y_0} \frac{1 - y}{y} \right)^{P_n} \qquad (7)$$

where S is the concentration in the surge, and S_0 is the concentration at the base. The other parameters in the equation are the same as those mentioned above. Using equation (7), we can calculate the relationship between the particle concentration S and the height of the current y, and then obtain the concentration profile within the base surge (Sun *et al.*, 2005).

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RECENT ADVANCES IN STUDY ON IMPACT OF VOLCANISM ON ENVIRONMENT AND CLIMATE CHANGES IN CHINA

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ABSTRACT: There are large-scale intermediate-acidic explosive volcanic eruptions in China; they may have emitted huge amounts of volatiles and resultant aerosols into atmosphere and led to paleo-environment and climate changes. On the basis of depictions of analytical techniques of volcanic volatiles and estimations of the total mass, we review recent advances on the effects of intermediate-acidic explosive volcanism on paleo-environment changes and mass mortalities of vertebrate. This contribution focuses on environmental effect of the Mt. Changbai volcanic eruption around 1000 years ago and Mesozoic intermediate-acidic volcanism in western Liaoning province, northeastern China. Mt. Changbai, located on the boundary between China and North Korea, is the largest active volcano in China, which is characterized by comenditic Plinian fallout and unwelded ignimbrite. Mesozoic intermediate-acidic tuff and tuffites, interbedded with lacustrine deposits, yield well-preserved vertebrate fossils in the western Liaoning volcanic field, which has been regarded as a natural laboratory exploring relationships between volcanic activities and mass mortalities. Ongoing studies (e.g., Mesozoic-Cenozoic Linzizong volcanism in Tibet and Emeishan flood basalts in SW China) will contribute much valuable evidence for global environmental change studies.

KEYWORDS: Intermediate-acidic explosive volcanism, volatiles and aerosols, paleo-environment and climate, mass mortality of vertebrate, petrologic method, China.

I. INTRODUCTION

Volatiles erupted from large-scale explosive volcanic activities have a significant impact on climate and environmental changes (Sigurdsson, 2000). Three factors are responsible for extents of environmental effect of volcanism: compositions and amounts of volatiles released, and maximum heights of volcanic eruption columns. Different compositions of volatiles released may result in variable trends of climate and environmental changes. Amounts of erupted volcanic gases and resultant aerosols would be responsible for intensities of climate and environmental changes (Sigurdsson, 2000). Maximum heights of volcanic eruption column could constrain temporal and spatial scopes of volcanogenically environmental and climate changes (Horn and Schmincke, 2000; Schmincke, 2004). Quantitative assessment of composition and amounts of volcanogenic volatiles and resultant aerosols is critical for studying its climate and environmental effects based on estimations of maximum height of eruption column by approach of isopleths of clast distribution. This requires a combination of physical with chemical volcanology. This work focuses on recent advances in effect of Mesozoic-Cenozoic, intermediate-acidic, explosive volcanism in China on paleo-environment and climate changes based on determination of composition and amount of volcanic volatiles released.

II. ANALYTICAL TECHNIQUES OF VOLCANIC VOLATILES

2-3 kg fresh samples of Plinian fallout tephra and/or ignimbrites collected are cut into slips and then observed under microscope, and phenocryst mineral assemblies are determined. Previous studies (e.g. Guo et al., 2002, 2003c, 2006; Li and Wu, 2004) have indicated that phenocrysts of intermediate-acidic Plinian fallout tephra and ignimbrites in China are mainly composed of olivine, pyroxene, amphibole, biotite, plagioclase, anorthoclase, sanidine and quartz. Melt inclusion in late-phase phenocrysts (e.g. anorthoclase, sinidine and quartz) and co-existing matrix glasses, based on petrographic observations, would be prepared for volatile composition analysis by electron microprobe. Melt inclusion in phenocrysts for analysis should be primary and colorless (Guo et al., 2002). Detailed characteristics of melt inclusions and matrix glasses analyzed are in accordance with criteria in the references (Horn and Schmincke, 2000; Guo et al., 2003c; 2006). Analyses of major element oxides and volatile components (e.g. F, Cl and S) were carried out by CAMECA SX51 electron microprobe. Analytical conditions (Guo et al., 2006) were: 15 kV accelerating voltage, 5-20 nA current, 1-10 μm electron beam in diameter for melt inclusion and 10-20 μm for matrix glasses; relative analytical precision was F<2%, Cl<4% and S<5% on the basis of repeated analyses of international standards. More detailed procedures follow descriptions of references (Guo et al., 2002; 2003c; 2006). Total H_2O contents of melt inclusions and matrix glasses were estimated by difference between the total of an electron microprobe analysis and 100% (so called "difference method") (Guo and Liu, 2002a; Guo et al., 2003c). Relative proportion of S^{6+}/S_{total} was determined on the basis of determinations of shift of S kα wavelength peak position. Detailed studies on analytical methods of other volatiles (e.g. CO_2) may see the references (e.g. Zhang et al., 2000; Li et al., 2006).

III. ESTIMATIONS OF TOTAL MASS OF VOLCANIC VOLATILES

Previous studies (e.g. Guo et al., 2002; 2003c; 2006) have shown that concentrations of volatiles in melt inclusions of host mineral crystals may represent contents of volatiles in magmas prior to eruptions and those of volatiles in matrix glasses may represent contents of volatiles in magmas after eruptions. Differences between contents of volatiles in the melt inclusions and co-existing matrix glasses have been believed to be concentrations of volatiles erupted from volcanic activities.

"Petrologic method" (Guo and Liu, 1998; Zhang et al., 2000; Guo et al., 2002; Guo et al., 2003a; Li and Wu, 2004) has been considered to be the best approach to estimate total mass of volatiles released from volcanism (M), especially for (geologic) historic eruptions, because it is not easy to estimate total mass of volatile emissions by direct instrument observations. The "Petrologic method" indicates that total eruptive mass of volatiles is in direct proportion to difference of volatile contents of pre- and post-eruption (m), melt density (D), melt abundance (A) and total volume of dense rock equivalent (DRE) volume (V). The mathematics relation for the model is as follows: $M=m\times D\times A\times V$.

Detailed determination processes of above parameters may see references (Guo et al., 2002; Guo et al., 2003a; Guo et al., 2006)

Recent studies on effects of explosive volcanism on paleo-environment and climate changes in China focus on the Mt. Changbai volcano erupted around 1000 years ago and Mesozoic volcanism in western Liaoning province (Fig. 1). We review research works as follows, which were originally published in Chinese literatures.

IV. EFFECT OF VOLATILES ERUPTED FROM MT. CHANGBAI ACTIVE VOLCANO ON ENVIRONMENT AND CLIMATE CHANGES

Cenozoic volcanism in the Mt. Changbai area (Fig. 1) generated three types of volcanics, which are Paleogene basaltic lava on the bottom, Pleistocene trachytic and comenditic volcanic rocks in the intermediate parts, and Holocene comenditic Plinian tephra and ignimbrites on the top (Fan et al., 1999; Liu, 1999). Previous studies (Liu, 1999; Wei et al., 2004; Fan et al., 2006) have shown that there were more than five times of eruptions of Mt. Changbai volcano in the historical times. One of the largest eruptions during the Holocene occurred in about 1000 years ago (Li et al., 2000; Wei et al., 2003). The volcanic ash erupted have been recognized in Japan based on geologic and geochemical correlations (Machida and Arai, 1983), which is more than 1000 km from the Mt. Changbai volcanic vent. Moreover, much far spatial scope of volatiles released from this eruption has been approved to arrive in Greenland (Zielinski et al., 1994). Previous studies on Mt. Changbai volcano (e.g. Wang et al., 2000; Li et al., 2004; Wei et al., 2004) mainly concern with geologic, petrological, geochemical and physical volcanology, and hazard assessment, which have provided bases and possibilities for studies on environmental effects of Mt. Changbai volcanic eruptions.

Previous studies (Firth and McGuire, 1999; Sigurdsson, 2000) indicated that significant volcanogenic F and Cl may form poisonous HF-rich cloud and cause ozone depletion and even “ozone hole” in the atmosphere, respectively. Volcanic erupted S would lead to the surface temperature decline and acid rain (Oppenheimer et al., 2003). Early studies on environmental effect of the Mt. Changbai volcanic eruptions (Horn and Schmincke, 2000; Li and Liu, 2000; Guo et al., 2002) have mainly focused on the determination of composition and concentration, and total mass of volatiles released, showing that Mt. Changbai active volcano has erupted significant mass of volatiles (e.g. Cl and F, and S). Contents and total mass of volatiles erupted from the Mt. Changbai volcano are higher than most catastrophic active eruptions worldwide based on comparisons (Guo et al., 2002). Thus, Mt. Changbai volcano may have led to heavy environment changes by ozone depletion, pollution of water and plants and temperature decline. Numerical simulation results (Li et al., 1996; Wei et al., 1997) indicate that stratospheric aerosol caused by this eruption may exist ~3 years and significantly influence on solar radiation.

Recent studies (e.g., Guo et al., 2006) have indicated that contents of volatiles emitted from the Mt. Changbai active volcano are characterized by cycled variations from early to late period. Concentrations of volatiles may be divided into two cycles and each cycle has similar variation trend with time. The cycle shows decreasing contents of F, Cl and H_2O emitted and increasing contents of S erupted; concentrations of SiO_2 and Cl/S ratios in melt inclusions show decreasing trend from early to late stages. This has been explained to result from replenishment of basaltic magmas because basaltic magmas have higher S contents and lower contents of Cl, F and H_2O than SiO_2-rich rhyolitic magmas (e.g. Guo et al., 2006). Input of high temperature basaltic melts into overlying intermediate-acidic magma chamber would trigger Mt. Changbai volcanic eruption and cause compositional zone of the volcanic products. This suggests that Mt. Changbai future eruption will follow the cycle-type trend and enter next new eruptive cycle.

Previous studies (e.g. Leonard et al., 2002) indicated that eruption in following cycle would show high explosive energy and cause disaster volcanic hazard and environmental effect if duration of gap between two cycles is much longer because larger volume of silicic magmas may be aggregated in upper part of magma chamber. Detailed field observations showed that there is no weathering between two cycles in Mt. Changbai volcanic field, indicating that gap duration between the two-cycle eruptions is short. However, it has elapsed ~1000 years since the second cycle of eruption in the Mt. Changbai volcano, which likely is longer than gap duration between the two cycles of eruptions studied. Moreover, there is no silicic lavas erupted in Mt. Changbai since the largest volcanic activity in historic times. This indicates that potential environmental effect and hazard caused by future Changbai volcanic eruption will be more serious than the largest eruption ~1000 years ago if its eruption product is also SiO_2-rich magma (Guo et al., 2006).

1. Effect of Volatiles Erupted from Mesozoic Volcanic Activities in Western Liaoning Province on Paleo-Environment Changes and Mass Mortalities of Vertebrate

Western Liaoning province (Fig. 1) is complicated by two groups of Mesozoic tectonics; their strikes are in E-W and NNE-SSW directions. This area was also characterized by intensive, Mesozoic, intermediate-acidic volcanism (Chen and Chen, 1997). Detailed field studies (e.g. Guo and Wang, 2002; Guo et al., 2003b) indicated that there are more than fifty layers of tuff and tuffites intercalated with lacustrine deposits and the intermediate-acidic volcanic layers have yielded superbly well-preserved vertebrate fossil assemblages (e.g. fishes, frogs, turtles, feathered dinosaurs, primitive birds, mammals and the earliest Angiosperm *Archaefructus*) and invertebrate fossils (e.g. shrimps, insects, bivalves, conchostracans, ostracods, gastropods and salamanders) and plant fossils. This has provided valuable evidence for further study on origin of birds and bird-dinosaur links. $^{40}Ar/^{39}Ar$ dating of sanidine phenocryst in the tuffs gave an age of 124.6 Ma (Swicher et al., 1999). Field and excavating works (e.g. Guo and Wang, 2002; Guo et al., 2003b,c; Jia et al., 2004) have concluded that the fossil-rich layers represent records of mass mortality events of vertebrates and the fossils extremely well preserved in the tuff, tuffaceous sandstone, tuffaceous siltstone, tuffaceous mudstone and shale indicate potential relations of the mass mortalities with volcanic activities.

Guo et al. (2003b, c) measured compositions and concentrations of volatiles erupted from volcanic activities in this area, showing high emissions of volatiles compared with huge active volcanoes worldwide causing substantial effect on climate and environmental changes, and indicated much higher contents of volatiles released from the eruptions represented by volcanic deposits yielding the fossil-rich layers than those indicated by tuffs and tuffites of fossil-poor layers. Moreover, volumes of eruptive products and maximum heights of eruption columns are 200-320 km^3 and 18-38 km based on isopach and isopleth approaches, respectively (Guo et al., 2003c). This further supports the inference having a relation of explosive volcanic activities with mass mortalities.

In order to further explore environmental and climate changes caused by Mesozoic volcanism in western Liaoning province, Guo et al. (2003c) have grouped volatiles released from volcanic activities into three types based on their compositions and concentrations: (1) dominated by HF gas, (2) mainly composed of HCl gas, and (3) consists mainly of sulfur gases (e.g. SO_2 and H_2S). They have been considered to cause different climate and environmental effects shown below.

(1) Effect of HF emission on climate and environmental changes

Previous studies demonstrated that hydrogen fluoride would be responsible for the most lethal gas-related volcanic event (Sigurdsson, 2000). For example, sufficient HF gas was erupted from Hekla (Iceland) in 1766-68 AD and adsorbed on tephra, and transported hundreds of kilometers distance. People nearby have been seriously impacted by tephra fall and lethal fluorosis of livestock (Sigurdsson, 2000).

More than one thousand of primitive bird fossil specimens (e.g., *Confuciusornis*) have been found in the studied area, and more than 95% of which came from two layers of tuff that have highest concentrations of HF erupted. The *Confuciusornis* fossils in two tuff layers were preserved at a density of about one per 5~6 m^2, and even one per 1~2 m^2 in dense area (Guo and Wang, 2002), indicating a mass mortality event of primitive birds. All of the *Confuciusornis* skeletons were oriented in a same direction, and necks extended forward and wings stretched outward (Guo and Wang, 2002; Guo et al., 2003b), indicating that mass mortality abruptly occurred during flying of a large number of high density of primitive birds. The bird fossils were yielded in tuffaceous mudstone and tuff and preserved in articulation with both skeleton and soft tissue, including rectric, flight and down feathers intact, showing a rapidly burial process associated with intermediate-acidic volcanic activities (Guo and Wang, 2002; Guo et al., 2003b). This, together with volcanogenic HF hazards shown in active volcano, supports an inference of dense primitive bird fossils in the studied area caused by high-HF-release eruptions.

(2) Effect of HCl on climate and environmental changes

Injection of significant amounts of volcanic HCl gas into the stratosphere would have ozone-destroying effects (Horn and Schmincke, 2000; Sigurdsson, 2000). Furthermore, volcanogenic HCl may lead to acid rain (e.g., Kilauea, Masaya volcano) that would pollute plants, alter lake water chemistry and even cause collapse of food chains (Wingnall, 2001). Volcanic eruption has the highest contents of HCl emission in the studied area, represented by one-layer thick tuff yielding almost all kinds of vertebrates (e.g., dinosaurs, turtles and fishes) and invertebrates, indicating input of large quantities of HCl gas into atmosphere and disaster environmental effects. This led to a large scale of mass mortality and eventually generated many kinds of vertebrate and invertebrate fossils well preserved in the tuff. A great amount of volcanic ash and fallout would immediately fall and rapidly bury dead animal bodies, forming well-preserved fossil layer in the tuff. There are no any vertebrate fossils found overlying the tuff layer in the area, indicating that the eruption represented by fossil-rich Plinian deposits had have fatal effect on environmental changes and long-term destroyed ecosystem since then.

(3) Effect of SO_2 and H_2S on climate and environmental changes

Studies (Sigurdsson, 2000; Schmincke, 2004) on active volcanoes worldwide (e.g., Tambora 1815; Agung 1963; El Chichon 1982; Mt. Pinatubo 1991) have indicated that one of the most important features of environmental effects caused by S-rich eruptions is surface temperature decrease, and even forming "volcanic winters" (Rampino et al., 1988) because photochemical reactions may generate sulfuric acid aerosols and then affect radiation budget in the atmosphere (Li, 2000). Besides, resultant volcanogenic H_2SO_4 (i.e. acid rain) aerosols might destruct ozone layer in the stratosphere (Brasseur and Granier, 1992; Wingnall, 2001).

Five layers of tuff and tuffites yield a large number of theropod dinosaur (including feathered dinosaur) fossils (Guo et al., 2003c; Jia et al., 2004); they are extreme dinosaur fossil-rich layers in the studied area. Corresponding eruptions are characterized by the highest contents of sulfur gases emitted (Guo et al., 2003c). Guo et al. (2003b, c) indicated that significant decline of the surface temperature induced by volcanogenic sulfur gases (H_2S and SO_2) would be crucial reason of mass mortality of cold-blooded dinosaurs preserved in the five layers of tuff.

Additionally, there are a few studies concerning effect of erupted volatiles of volcanism in Tibet (e.g., Linzizong volcanic eruptions) (Guo, 1997), Shanwang (Shandong province) (Guo and Liu, 2002b; Guo et al., 2005), Zhangjiakou (Hebei province) (Guo and Liu, 1998) on environment and climate changes (Li, 2002), and the Emeishan flood basalts (LIPs) in SW China and its relation to mass extinction events on P-T boundary (Lo et al., 2002; Xu, 2002; Zhou et al., 2002).

ACKNOWLEDGEMENTS

This work was financially supported by the National Natural Science Foundation of China (NSFC) (Grant No. 40372045 and 40473023). Prof. M. Wilson is heartily thanked for her thoughtful and careful review, which has improved the manuscript. We are particularly grateful to Prof. Qicheng Fan for his comments.

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PHYSICAL AND CHEMICAL PROCESSES OF CRATONIC DESTRUCTION BENEATH EASTERN NORTH CHINA: MANTLE PERIDOTITIC EVIDENCES

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Abstract: Subcontinental lithospheric mantle (SCLM) in temporal and spatial, reflected by xenolith and terrane peridotites from eastern North China, are compared for the discussion on the cratonic destruction processes. The coexistence of the SCLM with refractory, transitional and fertile affinity cannot be well interpreted for the destruction by the mechanism of lithospheric delamination. Simple melt-peridotite interaction is difficult to interpret the depleted diopside-LREE patterns in the Cenozoic lithospheric mantle, that is, it is irreversible of the transitions of the complex cratonic mantle to the simple 'oceanic' lithospheric one. The complex processes including lateral spreading (extension), melt-rock interaction, asthenospheric erosion and mantle replacement, therefore, should be involved during the cratonic destruction (lithospheric thinning) beneath the eastern North China. These processes may include: 1) the northward subduction and subsequent collision of the Yangtze Craton in early Mesozoic would result in the North China SCLM experienced metasomatism or modification (melt-rock interaction) by fluids/melts derived from the subducted Yangtze continent, lithospheric extension and asthenospheric erosion; 2) the strong upwelling asthenosphere related to the subduction of the Kula and the Pacific Plates during late Mesozoic – Paleogene would progressively extend and erode the remained SCLM; and 3) the cooling of the upwelled asthenosphere in Neogene would slightly lowers the lithosphere-asthenosphere boundary, create newly accreted SCLM. The fertile peridotite xenoliths in the 100 Ma Fuxian basalts indicate that the early mantle replacement beneath the eastern North China Craton took partly place before the time.

Key words: Peridotite, Mantle nature, Cratonic destruction, Physical and chemical processes, Eastern North China

I. INTRODUCTION

Compared with the oceanic lithosphere, the continental one is older in formation age and obviously experienced mantle metasomatism [1]. The formation age of the subcontinental lithospheric mantle (SCLM) is generally consistent with its overlay crustal age when mantle and crust are coupled [2]. However, the strong interaction between asthenosphere and lithosphere could destroy the coupling [3-4]. The North China Craton is one of the regions of Eurasia continent which has a few Paleoarchean rocks [5-8]. It is well known and identified that the lithosphere beneath its eastern part had been thinned accompanying with mantle replacement during Mesozoic and Cenozoic times [9-16]. However, there are two contrasting explanations for the mechanism of cratonic destruction: lithospheric delamination [17-20] and asthenospheric erosion [21-25]. The 'delamination' emphasized the sinking of cold and heavy the lithosphere, corresponding to the 'sudden' physical process; the 'erosion' emphasized the hot asthenospheric upwelling, corresponding to the 'gradual' chemical process. Most recently, it is gradually recognized that the mantle extension is important on the cratonic destruction [21, 26]. Furthermore, it still has different recognition on the starting time [17, 27], dynamics [28-31], and mechanism [26, 32] of cratonic destruction. The study show that the complex processes including lateral spreading (extension), melt-rock interaction, asthenospheric erosion and mantle replacement should be involved during the destruction, and the mantle replacement took partly place before 100 Ma.

II. PARTIAL MELTING OF THE SCLM

The subcontinental lithospheric mantle (SCLM), composed mainly of peridotite, is normally considered as the remainder of the primitive mantle experienced the partial melting in different degrees forming basaltic melts, and second metasomatism. Thus, the compositions of the bulk-rock and its minerals may reflect the nature of lithospheric mantle and the deep processes it underwent. If the primitive mantle experienced high extraction, the remainder should contain less diopside and spinel/garnet, low $CaO+Al_2O_3$, high $Mg^\#$ (defined as Mg/(Mg+Fe)), and is composed of high $Cr^\#$ (defined as Cr/(Cr+Fe)) diopside and spinel/garnet. It denotes that the lithospheric mantle is ‘refractory’. In contrast, the ‘fertile’ mantle is lower degree of partial melting, and contains more diopside and aluminiferous minerals, and thus higher basaltic component ($CaO+Al_2O_3$), lower $Cr^{\#}$-diopside and spinel/garnet. In addition, two terms, such as ‘depletion’ and ‘enrichment’, are usually used on the studies of the lithospheric mantle to describe the degree of mantle metasomatism reflected by the incompatible trace elements. Theoretically, the mantle which only experienced the partial melting and did not affected by metasomatism would contain low content of incompatible trace elements and show LREE-depleted patterns; in contrast, the mantle modified by metasomatism would contain high contents of incompatible trace elements and show LREE-enriched patterns. The decoupling between the refractory (in major elements) and enrichment mantle (in incompatible trace elements) could appear due to mantle metasomatism. For example, the cratonic mantle with Archean age is usually refractory in major elements, also strong enrichment in the incompatible trace elements; in contrast, the Phanerozoic lithospheric mantle show fertile in major elements and depletion in incompatible elements [2, 21, 33].

Fig. 1 shows the distribution of $Mg^{\#}$ value of peridotitic olivines in temporal and spatial, from the eastern North China. The samples with olivine-$Mg^{\#}$ > 92 as refractory, <90 as fertile, and 92-90 as transitional are considered [34]. The majority of diamond inclusions and peridotitic xenoliths/xenocrysts in Paleozoic Mengyin (Shandong Province) and Fuxian (Liaoning Province) kimberlites are refractory with minor transitional and without fertile. The major refractory xenoliths can also be found in the Hebi Pliocene (4 Ma) basalts, where some transitional and fertile but ones can be found. The CCSD-PP1 peridotites from the early Mesozoic Sulu UHP terrane, as well as the xenoliths of the late Mesozoic (100 Ma) Fuxin and Junan (67 Ma) basalts are mainly transitional with a few refractory, and fertile which has low down to 86-87 olivine-$Mg^{\#}$. The regions with the majority of transitional peridotitic xenoliths include the Cenozoic Hannuoba (22 Ma), Qixia (12 Ma), Huinan (~3 Ma) and Kuandian (~1 Ma) basalts. Few refractory samples can also be found in the Hannuoba and Kuandian basalts. The xenoliths are mainly fertile from the late Mesozoic (74 Ma) Jiaozhou, and the Cenozoic Shanwang (16 Ma) and Nushan (<2 Ma) within the translithospheric Tanlu fault zone. There is a few refractory mantle existed in Nushan. These xenoliths obviously show us that the SCLM beneath the eastern North China is heterogeneous in temporal and special during the Mesozoic-Cenozoic times. The early Mesozoic (178 Ma) Xinyang peridotitic xenoliths had been strongly altered by major talc and minor serpentine, without the relics of fresh olivine and orthopyroxene. However, their refractory nature can be judged and estimated by the compositions of the relics of the co-existing diopside and spinel [29].

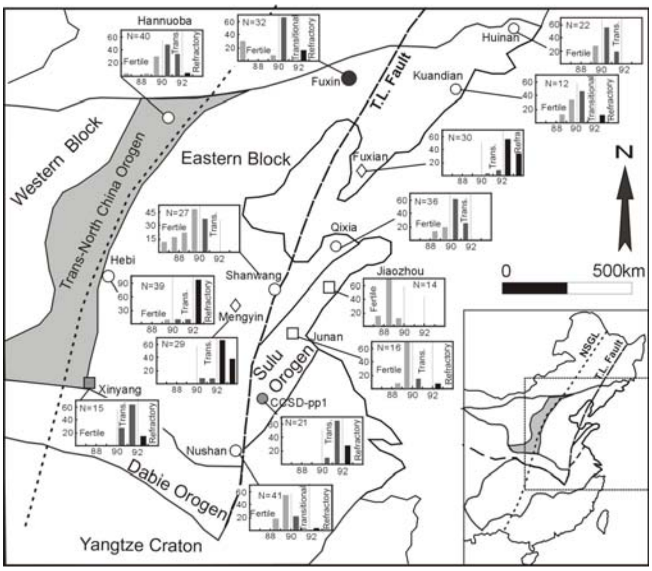

Fig. 1 Mg-number of olivine in peridotites from the eastern North China

Data source： Mengyin and Fuxian, Zheng（1999）[15], Zheng et al. (2006a) [34] and authors' unpublished data; CCSD-pp1 (the pre-pilot hole of the Chinese Continental Scientific Drilling Project) peridotites, Zheng et al.(2005b, 2006a, 2006b) [34-36]; Fuxin, Wang et al. （2002）[37] and authors' unpublished data; Jiaozhou, Yan et al.（2003）[38]; Junan, Ying et al. (2006) [39]; Hannuoba, Chen et al. (2001) [40], Rudnick et al. (2004) [41], Yu et al. （2006）[42]; Shanwang, Zheng et al. (1998, 2006a) [21,34]; Qixia, Zheng et al. (1998) [21], Rudnick et al. (2004) [41]; Hebi, Zheng et al. (2001) [33]; Huinan, Z and Zhao（1987）[43], Xu et al. （1996，2003）[44-45]; Kuandian, E and Zhao （1987）[43]; Nushan, Xu et al. (1998) [22]

III. METASOMATISM OF THE SCLM

In four-phase perdiotite, diopside usually records abundant partial melting and mantle metasomatism information due to its low melting temperature. The low HREE contents reflect the high degree of partial melting, and the high LREE contents record the strong mantle metasomatism. Diopsides with low HREE contents and obvious LREE-enriched mainly include those from Paleozoic to early Mesozoic samples, i.e., the Mengyin xenoliths/xenocrysts, the

Fuxian diamond inclusions, the Donghai UHP terrane, and the Xinyang xenoliths. The Hebi peridotites captured by Cenozoic (4 Ma) basalts can be subdivided into two groups [33]: major high-olivine $Mg^{\#}$ and minor low-olivine $Mg^{\#}$. The Hebi mantle diopsides contain low HREE contents and show the LREE-enriched patterns with the sinusoid shape, suggesting the processes including primary depletion, second enrichment, and re-depletion. LREE-enriched diopside can also be found in the late Mesozoic Junan (one sample), and in the Cenozoic Hannuoba, Kuandian and Nushan xenoliths. In contrast, the diopside with high HREE content and LREE-depleted to obviously enriched patterns can be found in all regions (but 4 Ma Hebi) within the eastern North China since late Mesozoic (~100 Ma) Fuxin basalts.

The content and relationship of the trace elements of diopside in the 'dry' perdiotite is a good to "fingerprint" whether or not the lithosphere experienced mantle metasomatism and the metasomatic agents [47-48]. The plots of (La/Yb)n against Ti/Eu is usually used to distinguish the agents, carbonatitic melt and silicate melt [49], which are common in mantle metasomatism. The high (La/Yb)n and low Ti/Eu are usually considered as the metasomatism by carbonatitic melt; in contrast, it is preferred to the metasomatism by silicate melt. As shown in Fig. 2, diopsides recording the mantle metasomatism by carbonatitic melt include those from the Paleozoic and early Mesozoic lithosphere, i.e., the Mengyin xenoliths/xenocrysts, the Fuxian diamond inclusions, the CCSD-pp1 UHP terrane peridotite, and the Xinyang peridotites. Most of the Hebi peridotites record the metasomatism by carbonatitic melt except few with low olivine-$Mg^{\#}$ by silicate one. In contrast, the diopsides captured by basalts after late Mesozoic (i.e. less than <100 Ma) usually reflect metasomatism by silicate melt (except Hebi), and only a few from Fuxin (one), Junan (one), Hannuoba (three), Qixia (two) and Kuandian (one) basalts reflect the metasomatism by carbonatitic melt.

IV. *IN SITU* RE-OS ISOTOPES

In situ Re-Os isotope analysis of sulfides with different occurrences was taken for three Hannuoba peridotitic xenoliths [50]. Sample JSB02-2 is a refractory sample, with 92.8 olivine-$Mg^{\#}$ and 23.5 diopside-$Cr^{\#}$ respectively. The sulfides as inclusions in olivine present consistent of T_{RD} (2.1 ± 0.6 Ga) and T_{MA} (2.2 ± 0.6 Ga). DMP02-9 is a transitional peridotite with 91.2 olivine-Mg#. The sulfides in the sample display as inclusions in minerals such as olivine and pyroxene and occurrence along cranny of the minerals. Those as inclusions give consistent of T_{RD} (1.3 ± 0.2 Ga) and T_{MA} (1.4 ± 0.2 Ga). Two sulfides as occurrence along cranny give 3.0-3.1 (± 0.3) Ga T_{RD} and 1.4-1.5 (± 0.1) Ga T_{MA}. DMP02-11 is a fertile peridotite with 90.6 olivine-Mg# and 9.3 diopside-Cr#. One grain sulfide occurred as inclusion yields 0.8 ± 0.4 T_{RD} and 1.2 ± 0.6 Ga T_{MA}. One as occurrence along cranny gives consistent of T_{RD} (0.7 ± 0.2 Ga) and T_{MA} (0.9 ± 0.2 Ga), but one gives 0.9 ± 0.1 Ga T_{RD} and 1.4 ± 0.1 Ga T_{MA} respectively. *In situ* Re-Os isotope data show that the deep processes in the SCLM are more complex than we imaged. The consistent T_{RD} and T_{MA} decrease with the olivine-Mg# decreasing.

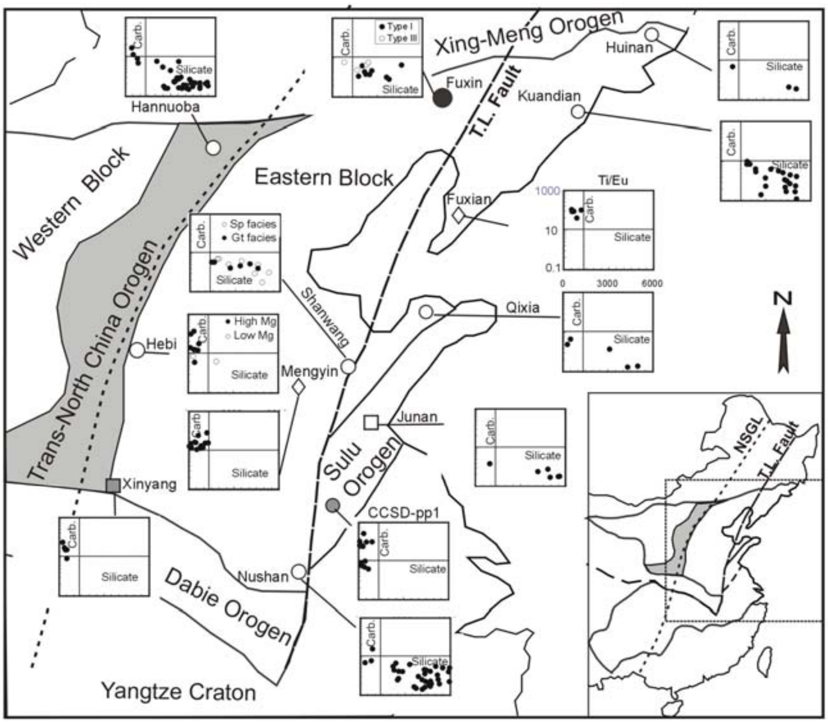

Fig. 2 Plots of Ti/Eu vs. $(La/Yb)_n$ of diopside in peridotites from eastern North China

Silicate and carbonatitic agents, Coltorti et al. (1999) [49]. Other data sources：Mengyin, Zheng et al. (2006a) [34]； Fuxian, Wang and Gasparik (2001) [46]; Xinyang, Zheng et al. (2005a) [29]; Fuxin, authors' unpublished date；Junan, Ying et al. (2006) [39]; Hannuoba, Chen et al. (2001) [40], Yu et al. （2006） [42]； Shanwang, Zheng et al. (1998, 2006a) [21,34]; Qixia, Zheng et al. (1998) [21]; Hebi, Zheng et al. (2001) [33]； Huinan and Kuandian, Xu et al. (2003)[45] and authors' unpublished data; Nushan, Xu et al.(1998) [22].

V. LITHOSPHERIC THINNING

5.1 Meso- (1.4 Ga) and Neoproterozoic (0.7-0.8 Ga) events beneath the NCC

Usually, it's hard to assess the SCLM age accurately by the Sm-Nd and Rb-Sr isotopic system. Re-Os isotopic system, however, is advantageous for revealing the formation and modification of the cratonic root [3, 51]. Four indicatory methods are used: 1) the Re-Os isochrone age, 2) the substitute isochrone age of Os isotopes [52], 3) mode age (T_{MA}), and 4) Re depletion mode age (T_{RD}) [53]. Gao et al. (2002) [54] and Xia et al. (2004) [55] reported the Re-Os isochrone and substitute isochrone ages for the Hannuoba peridotites, respectively. Both are Paleoproterozoic. The Os isotopes data of peridotites from the Cenozoic Qixia and Longgang basalts were Phanerozoic, recently given by Gao et al. (2002) [54] and Wu et al. (2003) [56]. Peridotitic sulfides, the main holder of Re-Os isotope in mantle xenoliths, show complex occurrences and thus different generations. It results in uncertain interpretation for the whole-rock ages [57-59].

Zheng et al. (2006) [26] presented the Re-Os isotope data of sulfide inclusions in olivine from two refractory peridotitic xenoliths in the Cenozoic Hebi basalts. Both have very consistent T_{RD} and T_{MA} (Table 1): one is Mesoarchean (3.0 ± 0.1 Ga), and the other is Neoarchean（2.5 ± 0.1 Ga）. These data further support the interpretation that the cratonic mantle has being persistent beneath Hebi area till Cenozoic, a locality at the western part of the eastern block in the North China Craton, far away from the translithospheric Tanlu fault zone [33]. The sulfides with different occurrences from three Hannuoba peridotites give various ages: 3.1-3.0 Ga, 2.2-2.1 Ga, 1.5-1.3 Ga and 0.9-0.7 Ga. The most often ages of the crustal rocks from the North China Craton are 3.1-3.0 Ga, 2.5 Ga and 2.2-2.1 Ga [5, 8, 60]. In contrast, the ages of 1.5-1.3 Ga (mean 1.4 Ga) and 0.9-0.7 Ga (mean 0.8 Ga) is rare to be found from crustal rocks in the same craton [60-61]. These show that the degree of modification in the cratonic mantle is much more complex than we imaged.

Generally, there is no zircon in peridotite due to its chemical component. However, the mantle metasomatism by melt/fluid derived from asthenosphere or released from the subducted lithosphere (dehydration) might change this situation [36, 62]. Liati et al. (2004) [63] first reported occurrence of zircon in a garnet peridotitic xenolith from South Namibia kimberlite. Zheng et al. (2006c) [61] progressively reported that U-Pb age, Hf isotope and trace elements of peridotitic zircons from the Xinyang early Mesozoic volcanic rocks at the southern margin of the North

China Craton. The zircons not only mainly record Triassic collision between the Yangtze and North China Craton, but also contain complex information with ages of 3.2 Ga, 2.3-2.4 Ga, 1.4 Ga and 0.7 Ga. These U-Pb ages are consistent with the sulfide Re-Os ages from the interior (i.e. Hebi) and the northern edge (i.e. Hannuoba) of the North China Craton. All of these ages support a fact that the cratonic lithosphere experienced multi-cycle mantle events [15], such as mantle modification due to the addition of the asthenospheric materials. These data also illuminate that in situ analysis is more advantageous than bulk-composition on expositing the lithospheric deep processes in detail, and revealing possible geothermal events of Meso- (1.4 Ga) and Neoproterozoic (0.7-0.8 Ga) beneath the North China Craton.

5.2 Delamination vs. co-existence of refractory, transitional and fertile mantle

It is widely accepted that about 150-200 km thick lithosphere in Paleozoic was greatly thinned beneath the North China Craton during Mesozoic-Cenozoic. Generally, delamination cannot take place for the cratonic lithosphere due to its low density and high buoyancy. However, it will begin in the following cases [27]: 1) the density of lithosphere exceeds asthenosphere’s when the cratonic lithosphere suffers strong collision from around blocks, 2) the buoyancy of craton lithospheric mantle is counteracted by the newly accreted lower crust in the crust-mantle transitional belt, or 3) the rheological condition of lithosphere was weakened adequately.

Assuming that the lithospheric mantle density of the North China Craton surrounded by the Sulu-Dabie and Xingmeng Orogens increased and exceeded the asthenosphere’s since the deep-subduction and collision of the Yangtze continent [64-65], the delamination should be happened in Early Mesozoic. However, the refractory peridotitic characters of the Sulu UHP terranes [34-35] and Xinyang xenoliths [29, 61] indicate that they have been exhumed (e.g. Donghai) or captured (e.g. Xinyang) rather than delamination, although the SCLM along the southern margin of the North China Craton was strongly affected by the subduction and collision of the Yangtze Craton. Meanwhile, there are a lot of high density rocks as xenoliths in Xinyang [66], such as high-pressure (HP) mafic granulite, eclogite and garnet pyroxenite, suggesting that the contribution of the delamination in Early Mesozoic is limited to the lithospheric thinning. On the other hand, assuming that the Yanshan intra-continental orogen could provide the rheological condition for weakening the North China Craton and the persistent delamintion including eclogite in lower crust happened, why did so abundant relics of the refractory (cratonic) peridotites in Hebi Cenozoic (4 Ma) basalts [26,33], and a few refractory mantle found in Fuxin (100 Ma), Junan (67 Ma), Hannuoba (22 Ma), Nushan (<2 Ma) and Kuandian (~1 Ma) areas (Fig. 1)?

Refractory relics or transitional mantle overlap the main fertile one in estimated temperature under the same pressure (i.e. 15 Kb, Fig. 3), indicating that three types of lithospheric mantle are crossed but there is no evident layer. Additional, the olivine-$Mg^{\#}$ values of the peridotitic xenoliths continuously vary at most regions (Fig. 1). The different occurrences of sulfides from the same xenoliths have different ages and record continual modification in SCLM. Therefore, delamination cannot well explain the fact of the old refractory merged with the newly accreted fertile mantle, or the existence of the abundant transitional mantle.

5.3 Melt-peridotite interaction vs. LREE-depletion of mantle diopside

More and more geological observation, petrology and geochemistry data, including the long magma activities, the high heterogeneity of lithospheric thinning in temporal and spatial, the lack of large volume basalts derived from asthenospheric mantle, all tend to support the ‘gradual’ thermal-chemical-mechanism thinning mode [14-16]. Among them, the interaction between peridotite and melt was considered as the main transitional mode of lithospheric mantle [28, 32]. The major sources of action melts are derived from crust and asthenospheric mantle. The melt-peridotite interaction changes the lithosphere constitutes and quick fertile mode [28, 32]. However, in fact, compared with the diopside in Paleozoic and Early Mesozoic SCLM, those in the peridotitic xenoliths from late Mesozoic (e.g. 100 Ma) usually contain high HREE contents, show weak LREE enrichment to even strong depletion and thus low (La/Yb)n values (Fig. 2). High HREE contents of diopside can be explained by the interaction between melt and peridotite [45]. However, the interaction is hard to explain generally appeared LREE depletion, that is, the transformation of the complex cratonic lithosphere with LREE enrichment Cpx to the simple ‘oceanic’ lithospheric mantle (with LREE depletion Cpx) [21-22]. On the other hand, the product from the peridotite-melt interaction should be lithospheric mantle rather than asthenospheric one. The simple peridotite-melt interaction can not well explain the huge lithospheric thinning beneath the North China Craton during Mesozoic-Cenozoic [1-2], therefore, other processes should be involved.

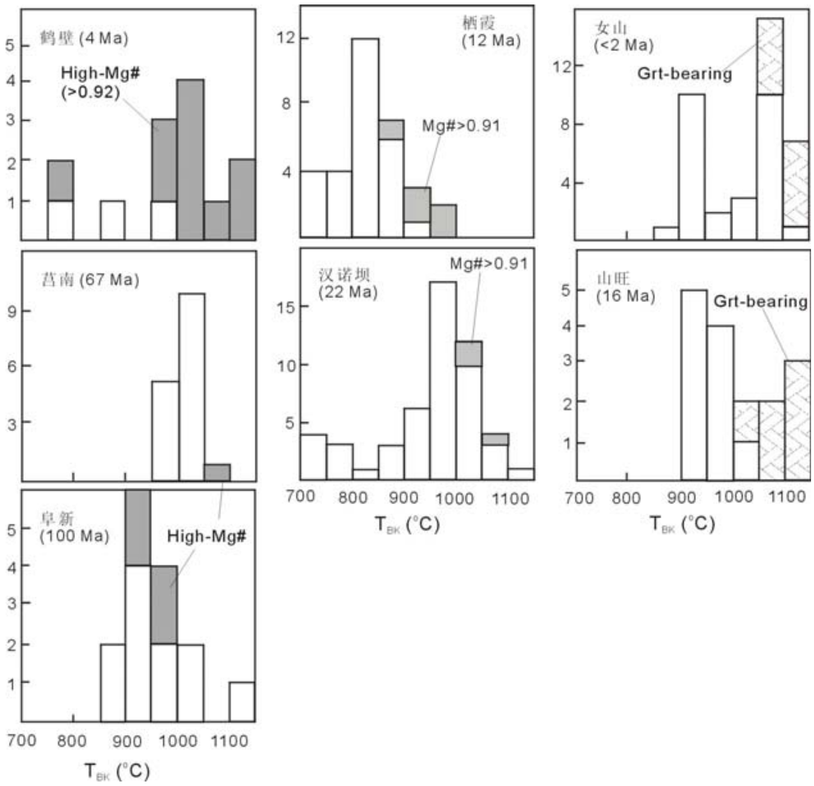

Fig. 3 Equilibrium temperature estimates of peridotite xenoliths from the eastern North China

Temperature estimates using the method of Brey and Köhler (1990) [67] under 15 kb. Other data sources：Junan, Ying et al. (2006) [39]; Hannuoba, Song and Frey (1989) [68], Fan and Hooper (1989) [69], Chen et al. (2001) [40], Rudnick et al. (2004) [41]; Shanwang, Zheng et al. (1998, 2006a) [21,34]; Qixia, Zheng et al. (1998) [21], Rudnick et al. (2004) [41]; Hebi, Zheng et al. (2001) [33]; Nushan, Xu et al. (1998) [22].

5.4 Complex processes during the North China cratoinc destruction

Compared with other cratons in the world, the North China Craton is relative small in size. Thus, it is easily affected by the subduction and collision from the plates around the craton. For example, the north-ward subduction of the Yangtze Craton and subsequent collision with the North China Craton in Triassic, would result in: 1) the metasomatism of the southern margin of the North China Craton (e.g. Xinyang) by melts or fluids released from the subducted lithosphere,

2) forming deep extrusion (Early) and shallow extension (Late) tectonic frame and part of the modified cratonic mantle involved in the Dabie-Sulu ultrahigh-pressure (UHP) metamorphism as tectonic ‘cold’ intrusion, and 3) the disturbed upwelling asthenospheric materials eroded the destroyed lithosphere. At this stage, except that the mantle extension caused the lithospheric thinning of the North China Craton, the melt/fluid releasing from the subducted Yangtze continent interacted with the peridotites may cause the change of mantle composition [28, 32], and form the source of comprehensive cal-alkalic magmatism in Mesozoic. Till and after the late Mesozoic (e.g., 100 Ma), the tectonics of the North China belongs to part of the eastern edge of Eurasia continent, which was further affected by heat perturbation caused by the subduction of the Pacific Plate [31]. Since it is hard to achieve transformation of the complex cratonic mantle with evolvement history (obviously refractory in major elements and strong enrichment in trace elements) to the obviously simple ‘oceanic’ lithospheric mantle (fertile in major elements and depletion in trace elements) through only peridotite-melt interaction, therefore, strong asthenospheric upwelling which eroded the lithosphere (a huge thinning) and then slightly cooling of the upwelled asthenosphere (a little thickening) should be important for the late Mesozoic-Cenozoic lithospheric thinning accompanying with mantle replacement, except the mantle extension due to the subduction of the Pacific Plate. The mode is effective to explain geochemistry of peridotitic xenoliths from the Late Mesozoic-Cenozoic basalts. For example, there are a lot of diopsides with LREE-depletion patterns in the newly accreted mantle, derived from the cooling of the upwelling asthenosphere, and some of them suffered partial melting and mantle metasomatism. About the starting time of mantle replacement, it is quite different. The reason is that the channel [15] shown by the mantle weak zone within the cratonic lithosphere is irregular. The irregular channel will lead the moving of basalts derived asthenosphere and thus different basaltic eruption ages. The Fuxin basalts erupted at around 100 Ma. The peridotitic xenoliths captured by the basalts are mainly fertile and newly accreted, indicating that the mantle replacement beneath the eastern North China Craton had carried out before the time.

VI. SUMMARY

In situ analysis is more advantageous than bulk-composition on revealing the details of lithosphere processes, and shows the existence of Mesoproterozoic (1.4 Ga) and Neoproterozoic (0.7-0.8 Ga) thermal events beneath the North China Craton. Lithospheric delamination cannot well interpret the coexistence of the refractory with the transitional and the fertile lithospheric mantle. Simple peridotite/melt interaction is also hard to explain the diopside with LREE-depletion patterns in Mesozoic and Cenozoic lithospheric mantle. Therefore, the lithospheric thinning (cratonic destruction) beneath the eastern North China Craton should include complex processes, such as mantle extension, melt-rock interaction, asthenospheric erosion and mantle replacement. There may be: 1) in early Mesozoic, the northward subduction and collision of the Yangtze continent caused mantle metasomatism and lithospheric extension of the North China Craton as well as the disturbed asthenospheric upwelling and eroding the modified lithosphere; 2) during the late Mesozoic-early Tertiary, the thermal disturbing due to the subduction of the Pacific Plate led to asthenosphere strongly eroding SCLM and thus caused huge lithospheric thinning, and 3) since late Tertiary, the cooling of the upwelling asthenosphere caused a slight lithospheric thickening. The first huge thinning of the lithosphere and then a slight thickening finally accomplished the mantle replacement. The peridotitic xenoliths captured by the Fuxin basalts erupted at 100 Ma are main fertile, indicating that at least part of the eastern North China Craton had carried out the mantle replacement before the time.

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MAGMA UNDERPLATING FORMED NEW CRUST-MANTLE TRANSITION ZONE —EVIDENCE FROM HANNUOBA XENOLITHS, NORTH CHINA

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ABSTRACT

Magma underplating is one of the essential mechanisms to the geodynamic evolution of the North China Craton in Mesozoic. It is well known that the lithosphere of North China destructed and lost most of its thickness in Mesozoic, thinned from ca. 200 km to less than 80 km, and hence the Paleozoic stable craton of North China was reactivated in Mesozoic. Hannuoba xenoliths, including granulite facies and eclogite faceis, reveal the occurrence of magma underplating in North China, and keep rich records of formation and evolution of the crust-mantle (CM) transition zone, so it takes an important role in the study on the lithospheric dynamics of North China. In this paper, we reviewed our recent works on Hannuoba xenoliths and its significance to the lithospheric evolution of North China.

KEYWORDS: North China, Hannuoba xenoliths, magma underplating, CM transition zone

I. INTRODUCTION

Origin and evolution of the continental crust is one of main targets to understand the geodynamics of lithosphere. Crust came into being at least before 3.8 Ga, and in the long history of the Earth, episodic growth occurred in the continental crust, as well as destruction and recycled. As a good case of reactivated tectonics (Chen，1996), continental craton destruction (Carlson et al., 2005) and large scale of lithosphere thinning (Menzies et al., 1993), evolution of North China lithosphere provides chances and challenges to understand the geodynamics of the Earth’s interior.

As one of oldest continents in the world, the North China Craton formed in Archean, and its rocks dated back to 3.6 Ga (Zheng et al., 2005). According to the studies (Menzies et al., 1993) on diamonds from kimberlites in Shandong and Liaoning, in Paleozoic a thick lithosphere over 200 km occurred beneath North China, and its lithospheric mantle belonged to typical continental craton. However, the present lithosphere of North China is only about 60-80 km thick, which was revealed by geochemical studies on the Cenozoic basalts and xenoliths in North China (Fan & Hooper，1989；Fan et al., 2000; Rudnick et al., 2004) and also by geophysical surveys and explorations (袁学诚, 1996; Chen et al., 2006). Compared the lithosphere of North China in Paleozoic and in Mesozoic, Menzies et al. (1993) present the hypothesis of lithospheric thinning of North China.

Until now, such large scale destruction of lithospheric mantle has only been found in the North China Craton (Carlson et al., 2005). As a special case, lithospheric thinning and the subsequent dynamic evolution of North China is important to understand the lithosphere evolution of North China and the Earth’s interior. Actually, even in the 1950’s geologist have recognized and studied the phenomena of the big change and destruction of the stability of the North China Craton, and called it reactivated tectonics (Chen, 1996). Like most of the craton in the world, the North China Craton is an old and tectonic stable continent. But great changes occurred in the North China Craton in Mesozoic, major tectonic frame changed, large scale of magma activity occurred, many metal ore deposits formed (Yang et al., 2003; Zhai et al., 2006). Compared with the former research, the hypothesis of lithospheric thinning (Menzies et al., 1993) attracted eyes to the evolution of deep interior of North China lithosphere. After that, many studies focused on the dynamic evolution in the deep lithosphere of North China, and new hypothesises presented, such as thermo-tectonic destruction (Xu et al, 2001), magma underplating (Fan et al., 2005), delamination (Gao et al., 2004) and replacement (Zhai et al., 2006).

The revolutionary change of North China craton in Mesozoic attracted many researches from all over the world, and several hypothesizes described the different aspects of the event. Magma underplating, which formed the “new” CM transition zone, was presented mainly based on studies on Hannuoba xenoliths.

II. CENOZOIC BASALTS IN HANNUOBA AREA AND XENOLITHS

Basalts and xenoliths are records of the earth’s interior, and take an important role in the studies of the lithosphere evolution of North China. The Hannuoba basalt (Liu et al., 1992; Xie et al., 1992) located in the northern margin of North China and the southeast margin of Mongolia plateau, mainly distributed in Datong, Zhangjiakou, Weichang and Chifeng, belonged to later Tertiary volcanic. The Hannuoba basalt was typical flood basalt, formed a wide lava plateau ca. 20 000 km^2. In the southern margin of the lava plateau occurred a series cross sections of basaltic successions, with many xenoliths from the lower crust and the lithospheric upper mantle. Volcanic successions of the Hannuoba basalt contain 20-30 layers of alkali basalt and tholeiite.

Although alkali basalt and tholeiite equally dominated in Hannuoba area, xenoliths only occurred in alkali basalts, just like most cases in the world. Sizes of xenoliths vary from centimeters to several ten centimeters, and olivine xenoliths over one meter can also be found. Hannuoba xenoliths, especially xenoliths of eclogite facies, igneous pyroxenite and high temperature mafic granulite facies, revealed the significance of magma underplating in lithosphere evolution of North China, and also revealed formation and evolution of the CM transition zone beneath Hannuoba (Fan et al., 2005).

III. COMPOSITION AND STRUCTURE OF THE CM TRANSITION ZONE

III.1 LOWER CRUST

In Hannuoba xenoliths (Fan et al., 1996), typical lower crust rocks are high-temperature granulite facies (HTGF), including websterite, clinopyroxene granulite, hypersthene granulite, and few garnet bearing granulite. Minerals composed of the granulite xenoliths are plagioclase, clinopyroxene, orthopyroxene, garnet and quartz (Plg ±Cpx±Opx±Gt±Qz). In websterite, which dominates the granlite facies xenoliths and hence the lower crust, typical mineral assemblages are pl±opx±cpx. Minerals of orthopyroxene in the HTGF xenoliths are hypersthene (average $Wo_1En_{73.4}Fs_{25.6}$). Compared to the terrain high-pressure granulite in North China, the HTGF xenoliths are enriched in MgO and depleted in FeO; and compositions of orthopyroxene in the HTGF xenoliths are also enriched in MgO and depleted in FeO, with higher compositions of Al_2O_3, Al^{VI} and Na_2O than the terrain granulite (Fan et al., 2005). Only in few granulite facies xenoliths, there are minerals of garnet (mainly almandine, $Pyr_{33\text{-}59}$), which are different from garnet (Pyr_{73-83}) in eclogite facies xenoliths (Fan et al., 2001, 2005).

Estimation of P-T conditions provided information of original depth of xenolith in lithosphere.

According to the mineral compositions, Fan et al. (1996) calculated the balance pressure of the HTGF, which were 1.0-1.3 GPa (about 33-40 km deep). High-temperature and high-pressure experiments (Fan et al., 2002) revealed that the in situ *p* weave velocity of HTGF xenoliths were 7.17-7.29 ms^{-1}, which is higher than that of terrain granulite, and in the range of CM transition zone (6.8-8.1 ms^{-1}) based on geophysical exploration.

The discovery of the HTGF xenolith in Hannuoba and the subsequent studies on it was important to understand the lithosphere evolution of North China. It was just the studies on the HTGF xenoliths induced the concept of magma underplating to describe the evolution of the lower crust in beneath Hannuoba (Fan et al., 1996), and further works indicated that magma underplating also controlled the evolution of CM transition zone (Fan et al., 2001). Petrological works on the Hannuoba xenoliths revealed the characteristics of magma underplating, such as banded structure (bands color mineral distributions), igneous structure and remnant of gabbro structure. Chemical compositions of the HTGF xenoliths were equivalent to mafic magma, with SiO_2 compositions of 45-55 wt%，$Mg^{\#}$ (= MgO/(MgO + totalFeO)) 60-90 wt%，and dominated by mafic minerals (Cpx+Opx > 50%). Petrological structure and geochemical compositions revealed that magma underplating formed the HTGF xenoliths in Hannuoba, this fact indicated that the lower crust was “newly” formed, not inherited from the old craton of North China. Compared to the terrain high-pressure granulite of the Archean craton, the HTGF xenoliths formed by magma underplating have characteristics of MgO enrichment (Fan et al., 2005).

Geochronoly of xenoliths proved the “newly” formed characteristics of the HTGF xenliths, which had two groups of ages as ca.140 Ma and ca.120Ma, based on U-Pb dating of zircons (Fan et al., 1998). The young age of the lower crust showed dramatic contrast to the over 3.6 Ga old history of North China craton. The two ages were described as two major events of magma underplating, in 140 Ma considerable magma underplating occurred in Hannuoba, and in 120 Ma large scale ofmagma underplating took place again, with major metamorphism of granulite facies (Fan et al., 1998, 2005). Anyway, the isochron ages proved that magma underplating new lower crust in the old craton of North China. If we took the “newly” formed lower crust of ca. 7 km thick (33 km - 40 km) as a kind of crust growth in vertical, then HTGF xenoliths demonstrated significant crust growth under the general background of lithosphere thinning in North China. From 140 Ma to 120 Ma, crust thickened ca. 22% in about 20 Ma. If we considered the magma underplating in CM transition zone as a trend of crust growth, then the thickness of crust growth was up to12 km (ca. 5 km CM transition zone in Hannuoba, see Fan et al., 2002).

An other achievement on the HTGF xenoliths in Hannuoba was the discovery of oceanic geothermo gradient characteristics of the continental craton of North China (Fan et al., 1996), which indicated that the North China craton was quite different from other cratons in the world. The balance temperature of the mafic xenoliths in Hannuoba were 900-1000℃, about 100-150℃ higher than the terrain high-pressure xenoliths in North China, so it was called high-temperature granulite facies (Fan et al., 1996). The fact indicated that the cold and thick lithosphere changed to warm and thin in Mesozic.

III.2 CM transition zone

Rocks of the CM transition zone in Hannuoba based on xenoliths were a series of hybrid rocks of eclogite facies formed by magma underplating and mantle peridotite, including spinel peridotite, eclogite facies garnet pyroxenite (EFGP) and igneous pyroxenite (Fan et al., 2001, 2005). Spinel peridotite was typical rocks of the upper mantle, while the EFGP xenolith was formed by magma underplating. In Hannuoba xenoliths, the EFGP was covered in peridotite as thin veins of ca. 10 cm, this characteristics revealed that the CM transition zone was composted by hybrid rocks of different facies, not unique facies. The EFGP had banded structure of igneous accumulation, which revealed that small vein of magme intruded in the upper mantle and experienced slow cooling and crystallization. If the layers of accumulation were always vertical to the direction of gravity, then the EFGP layers present the horizontal direction. Hence the structures of the CM transition zone were characterized by thin, horizontal veins of EFGP mixed in the peridotite.

Typical mineral assemblage of the EFGP were Gt＋Cpx±Opx, no plagioclase (Fan et al., 2002, 2005). Size of garnet varied from 1-8 mm, and erosion destroyed thoroughly almost all the garnets, and the remnant formed dusty spot. In the hand samples, it’s hard to recognize the geometry of garnet or typical characteristics of garnet crystal. Howerver, clinopyroxene crystal were fresh, with black or brownish black color, which were quite different form the green clinopyroxene in mantle peridotite. Estimation of the balance temperatures and pressures of minerals in EFGP xenoliths (Fan et al., 2002, 2005) revealed that were formed in 40-45 km (about

1.3-1.5 GPa), this depth equaled to the minimum depth of spinel peridotite. Hence the EFGP formed by magma underplating into the uppermost of the lithospheric mantle, and then the CM transition zone formed by the hybrid layers. The balance temperatures of the EFGP (Fan et al., 2005) were over 1000℃ (ca. 1065-1080℃), and eclogite facies metamorphism occurred in this pressure and temperature. The estimation of in situ *p* weave velocity of the EFGP (Fan et al., 2002, 2005) were 7.31-7.78 ms^{-1}, and the velocity of ordinary CM transition zone by geophysical explorations were 6.8-8.1 ms^{-1}. EFGP and peridotite composed a zigzag profile of *p* weave velocity in CM transition zone.

III.3 the lithospheric upper mantle

Ordinary, the lithospheric upper mantle were composed by ultramafic rocks. In Hannuoba, the rock types of the upper mantle were spinel peridotite and garnet lherzolite (Fan et al., 2002). Spinel peridotite, as a prevalent rock in lithospheric upper mantle, changes to garnet facies in higher pressure (ca. 55-70 km), so the original depth of the spinel peridotite should never deeper than this. Spinel peridotite took an important role of petrological standard of pressure in Hannuoba.

IV. DISCCUSSION

Moho, as abrupt of weave velocity on seizomology, separates crust and mantle. At first, Moho was presented based on geophysics of the Earth’s interior, and subsequent studies on petrology indicated that granulite facies dominated the lower crust and eclogite facies dominated the upper mantle, and rock facies changed from crust to mantle, not only weave velocity. Further studies indicated that a transition zone of granulite facies and eclogite facies occurred in active continental area, just like that in Hannuoba. Hannuoba xenoliths demonstrated a series variation on petrology, mineralogy, geology and P-T condition, from lower crust to upper mantle. It formed a typical CM transition zone, and its compostion, structure, magma underplating and other characteristics improved our understanding of the North China lithosphere and its evolution in Mesozoic.

Definitely the CM transition zone takes an important in CM reactivation and lithosphere evolution, however cross sections of CM transition zone rarely occurred in North China and in the world. Hannuoba xenoliths provided a big chance and challenge to reconstruct a systematic sections through the CM transition zone, based on fragments of lithosphere —xenoliths. Based on the study, some contributions to understanding the dynamics of North China craton and revolutionary evolution in Mesozic were made.

As to the macro structure of the North China lithosphere, the upper crust kept an old, Archean record of rocks (Zheng et al., 2005)；the major of the lower crust and the lithospheric upper mantle expericed thermo tectonic destruction, replacement and delamination (Xu et al., 2001; Zhai et al., 2006; Gao et al., 2004), it inherited compositions of the old lithosphere and also recorded the complex variation of evolutions; the CM transition zone formed by magma underplating in Mesozoic (Fan et al., 2005) was “newly” formed, without compositional heritage of old craton. Such vertical structure and variations of the North China lithosphere revealed that different part of depth recorded different evolutions, and hence the suitable hypothesis or stories should be different.

V. CONCLUSION

Our recent works on Hannuoba xenoliths made contributions to the revolutionary evolution of the North China craton in Mesozoic, studies indicated that: (1) xenoliths, as fragments of lithosphere, reconstructed a systematic cross section through the CM transition zone; (2) the CM transition zone was “newly” formed by magma underplating in Mesozoic; (3) magma underplating caused the crust of Hanuoba grew 7-12 km vertically, which was in dramatic contrast with the general background of lithospheric thinning.

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ADAKITES OR ADAKITIC ROCKS AND ASSOCIATED METAL METALLOGENESIS IN CHINA

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I. INTRODUCTION

The rock term "adakite" was firstly proposed by Defant and Drummond (1990). However, until 2000, about 10 years after the "adakite" was named, Chinese researchers began to pay attention to the study on adakites (Wang et al., 2000a, b; Xu et al., 2000). Since 2000, lots of papers on adakites or adakitic rocks in China have been published by Chinese and foreign researchers. Especially, during the last four years (2003-2006), significant advances have been made in petrogenesis of adakitic rocks and their associated Cu-Au mineralization. Here we summarize most of these achievements in this domain.

II. NOMENCLATURE AND CLASSIFICATIONS REGARDING TO ADAKITES OR ADAKITIC ROCKS

2.1 Nomenclature

Adakites were initially considered to be a kind of intermediate-acid and sodium-rich igneous rock, which are derived by partial melting of subducted young oceanic crust (Defant and Drummond, 1990). They are geochemically characterized by ≥56 wt% SiO_2, ≥15 wt% Al_2O_3 (rarely lower), low Y and HREE relative to normal island-arc andesite-dacite-rhyolites (ADRs) (for example, Y and Yb ≤ 18 and 1.9 ppm, respectively), high Sr relative to island-arc ADRs (rarely < 400 ppm), and high Sr/Y (≥40) and La/Yb (≥ 20) ratios. Their geochemical characteristics are indicative of garnet in their residual source.

Zhang et al. (2001a, b, 2003) considered that adakite is a suite of intermediate-acid igneous rocks characterized by heavy rare earth element depletion and no obvious negative Eu anomaly， indicating the derivation from very deep source with garnet in the residue. Zhang et al. (2001a, b, 2003) classified adakites into two types: one is O-type adakite，which is characterized by Na enrichment and in petrogenesis related to subduction process; another is C-type adakite，which is enriched in K (most of them are still enriched in Na，a few K-enriched), and is a product of partial melting of the lower crust granulite in the thickened crust resulted from underplating of basaltic magma. Wang et al. (2001a) also suggested that there are two types of adakites with different petrogenesis: one type is formed by the melting of subducting young (≤25~30Ma) slab (Ⅰ-type adakite), and another type is formed by the melting of basaltic lower crust under thickened setting (Ⅱtype adakite). Chung et al. (2003) and Zhai (2004) named the intermediate-acid igneous rocks derived by melting of thickened lower crust as adakites. Gao et al. (2004) named delaminated lower crust-derived intermediate-acid rocks as adakites. Dong et al. (2003) and Niu (2005) emphasized that the term “adakite” should only be used for the subducted-oceanic crust-derived intermediate-acid igneous rock in arc setting.

Wang et al. (2001b, 2003b, c), Xu et al. (2002), Xu and Wang (2003), Davis (2003), and Castillo (2006) named the intermediate-acid igneous rocks derived by melting of thickened (or delaminated) eclogitic lower crust as adakitic or adakite-like rocks, due to their geochemical characteristics similar to slab-derived adakites. Now, many Chinese scientists named the intermediate-acid igneous rocks (non-arc setting and non-slab melting) with geochemical characteristics similar to slab-derived adakites as adakitic or adakite-like rocks (e.g., Cai et al., 2004, 2005a; Gao et al., 2003a; Hou et al., 2004a, b, 2005; Lai, 2003; Su et al., 2004; Wang et al., 2005a; Wei et al., 2005; Wu et al., 2003b; Xiao et al., 2004; Xu et al., 2006a; Zhao et al., 2004b).

2.2 Other Classifications

Besides O-type and C-type adakites, Zhang et al. (2004d, 2005c) also proposed other classifications about adakites. Zhang et al. (2004d) classified adakites into the following six types: (1) typical adakite， which is derived from potassium—poor tholeiite or MORB and usually formed by subducted slab melting; (2) high—magnesium andesite，which is characterized by high $Mg^{\#}$ values and Cr and Ni contents; (3) TTG suite, which is diferent from typical adakite in that the Archean TTG suite is relatively enriched in Si and poor in Mg; (4) high-K calc-alkaline adakite, which is characterized by high K (Na_2O/K_2O close to 1) and low Mg, Cr and Ni content; (5) high-potassium and-magnesium adakite (HKMA); and (6) super-K adakite (SKA)with K/Na>1. Lately, Li et al. (2004) and Zhang et al. (2005c) also classified the intermediate-acid granitoids into five types based on their Sr and Yb contents: (1) high-Sr and low-Yb type (Sr>400 ppm, Yb<2 ppm), which is geochemically similar to adakites; (2) low-Sr and low-Yb type (Sr<400 ppm, Yb<2 ppm); (3) low-Sr and high-Yb type (Sr<400 ppm, Yb>2 ppm), (4) high-Sr and high-Yb type (Sr>400 ppm, Yb>2 ppm); (5) very low-Sr and very high-Yb type (Sr<100 ppm, Yb= 2-18 ppm).

III. THE SPATIAL AND TEMPORAL DISTRIBUTION OF ADAKITES OR ADAKITIC ROCKS IN CHINA

Zhang et al. (2003) summarized in detail the spatial and temporal distribution of adakitic rocks in China. They suggested that adakitic rocks occur geographically in most area of China except for Guangdong，Guangxi，Hunan and Guizhou Provinces and teconically mainly in the Paleo-Asian and Qin-Qi-Kun orogenic belts，Tibet Plateau, and east China. Recent (2003-2006) reported adakitic rocks also mainly occur above areas (Lai, 2003; Lai et al., 2003; Chung et al., 2003; Wang et al., 2003a, b, c, d, e, 2004a, b, c, d, e, 2005a, b, 2006a, b, c, d, e, f; Liu et al., 2003a, b, c, d; Gao et al., 2003a, b, 2005; Xiong et al., 2003, 2005; Li and Li, 2003, 2004; Jian et al., 2003; Xu et al., 2003, 2006; Qu et al., 2003, 2004a, b; Shi et al., 2003, 2005; Yuan et al., 2003, 2006; Cai et al., 2003, 2004, 2005a, b; Wu et al., 2003a, b; Zhao et al., 2003, 2004a, b, 2006; Pei et al., 2003; Xu and Wang, 2003; Mao et al., 2004a, b, 2006; Su et al., 2004; Zhu et al., 2004; Zhang et al., 2004a, b, c, 2005a, 2006a, b, c, d, e, f; Zhang and Zhang, 2005; Zhu et al., 2004; Hou et al., 2004a, b, 2005; Yang et al., 2005; Tao et al., 2005, 2006; Wei et al., 2005; Huang et al., 2005; Fu et al., 2005; Qin et al., 2005, 2006; Jin et al., 2005; Mao et al., 2005; Chen et al., 2005; Rui et al., 2006; Wan and Zhang, 2006; Luo et al., 2006; Xue et al., 2006; Jiang et al., 2006; Guo et al., 2006; Bian and Ding, 2006; Ke et al., 2006; Mo et al., 2006; Xiao et al., 2006; Yao et al., 2006; Zhou et al., 2006; Zeng et al., 2006; Niu et al., 2006).

The adakitic rocks in China have ages ranging from late Archean (2.5 Ga) to Miocene (~ 10 Ma). The oldest (2.5 Ga) adakitic rock occurs in the late Archean Wutai Complex, which is in the northern part of the North China Craton (Wang et al., 2004c). The youngest adakitic rock occurs in the southern Tibet (Chung et al., 2003). Neoproterozoic adakitic rocks occur in the NE Jiangxi, South China (Li and Li, 2003, 2004), Qingling Orogenic belt (Pei et al., 2003) and west Sichuan Province (Zhou et al., 2006). The Paleozoic (e.g., Liu et al., 2003b, c; Wang et al., 2003a, 2006a; Zhang et al., 2004a, b; Shi et al., 2005; Tao et al., 2005) and Paleozoic-Early Mesozoic (e.g., Shi et al., 2003; Jin et al., 2005; Qin et al., 2005; Wang et al., 2006d; Zhang et al., 2006c) adakitic rocks mainly occur in the Paleo-Asian and Qin-Qi-Kun orogenic belts, respecrively. Cenozoic adakitic rocks only occur in Tibet Plateau (e.g., Chung et al., 2003; Qu et al., 2004; Hou et al., 2004; Wang et al., 2005; Lai, 2003; Lai et al., 2003; Ke et al., 2006). But recent research reported some Triassic adakitic rocks in the margin of northern and eastern Tibet Plateau (e.g., Zhang et al., 2006d; Zeng et al., 2006). In east China, the adakitic rocks have late Mesozoic ages (e.g., Zhang et al., 2003a; Wang et al., 2003b, c, 2004d, e, 2006b, c; Xiong et al., 2003; Gao et al., 2004; Yuan et al., 2006; Cai et al., 2005b; Mao et al., 2004a, b; Li et al., 2006; Xue et al., 2006).

IV. PETROGENESIS OF ADAKITES OR ADAKITIC ROCKS IN CHINA

4.1. Tectonic Setting and Rock suites

4.1.1 Arc setting

Adakite-high-Mg andesite-Nb-enriched basaltic rock suites

Wang et al. (2003a, 2006a, 2007) found that Carboniferous adakite-high-Mg andesite-Nb-enriched basalts and basaltic andesite (NEB) suites occur in the Northern Tianshan Range (Xinjiang, northwest China) (e.g., Alataw, Dabate, Guozigou, Axi, Baluntai-Luotuogou, Tuwu-Yandong, and Chihu, etc.), were contemporary with ophiolites in the Bayingou area in the Northern Tianshan Range, and possibly represent arc magmas associated with the subduction of young and hot oceanic crust. Zhang et al. (2004a, 2005a) reported the early Devonian adakite-Nb-enriched basalt suites in north Junggar (Xinjiang), which were likely related to the subduction of the Palaeo-Asian oceanic crust in petrogenesis. Zhang et al. (2004g, 2005c) introduced the petrological and geochemical characteristics and geodynamics of sanukite, which is possibly associated with adakites in arc setting.

Adakites-ophiolites or mid-ocean ridge basalt (MORB)

Li and Li (2003, 2004) suggested that Neoproterozoic adakitic albite granites in the NE Jiangxi intruded approximately contemporary ophiolites, and were not generated during the processes of sea-floor spreading, oceanic crust shearing and obduction of fragmented oceanic lithosphere as previously thought, but during the process of subduction of oceanic lithosphere. Jian et al. (2003) and Liu et al., (2003b) found that the Early Paleozoic adakites occur in the Tulingkai ophiolite，Inner Mongolia，and were possible magmatic markers of the Early Paleozoic Ondor-Sum -Tulingkai subduction zone. Wang et al. (2004c) suggested that the Wutai Complex in Northern China Craton is a well-preserved Late Archean greenstone belt dominated by mafic, intermediate and felsic volcanic rocks, with a mid-ocean ridge basalt (MORB)-arc-back arc, basalt–adakite association.

Adakites

As suggested by Defant and Drummond (1990), most adakites, which were considered to have generated in arc setting by Chinese researchers, were not associated with contemporary basalts or high-Mg andesites (e.g., Zhang et al., 2003a, 2006a, e; Pei et al., 2003; Shi et al., 2003, 2005; Tao et al., 2005; Wang et al., 2006d; Xiong et al., 2005a; Xu et al., 2003; Yang et al., 2005; Zhou et al., 2006; Zhu et al., 2004; Zeng et al., 2006).

4.1.2 Extensional/contraction setting within continent

Zhang et al. (2003a) suggested that most adakitic rocks in the eastern China were generated in non-subduction setting. Gao et al. (2004) also considered that the Late Jurassic high-magnesium andesite-dacite-adakite suites in the Xinglonggou area of Northern China Block were generated in non-subduction setting. Davis (2003) thought that adakitic igneous rocks in the Yanshan belt of Northern China Block exhibit an extended period (ca.190-80Ma)，but the peak of such magmatism coincided with basement involved crustal contraction from ca 170-130 Ma.

Based on the close association of Late Mesozoic A-type granites, within-plate mafic rocks, a number of fault basins as well as other coeval metamorphic core complexes in southeast China (e.g., north orthogneiss unit of the Dabie orogen, Lushan and Wugongshan of Jiangxi province), Wang Q. et al. (2003c, 2004d, 2006b, c, 2007b) suggested that Late Mesozoic adakitic rocks in the eastern Yangtze Block were generated in an extensional tectonic regime within a continent. Moreover, Wang et al. (2006b) suggested that early Cretaceous adakitic and shoshonitic rocks in the Luzong area (eastern Yangtze Block) possibly represent a rock suite in an intra-continental extensional setting in contrast to similar rock suite in an arc setting (e.g., Defant and Drummond, 1990; Defant et al., 1991; Kepezhinskas et al., 1996). However, Wang Y. et al. (2004b) suggested that the eastern Yangtze Block was located in the inland portion of the arc during the early stage of early Cretaceous, and the adakitic magmatism in this area was possibly related to the oblique subduction of Izanaqi plate.

Xiong et al. (2003) and Cai et al. (2004) suggested that the late Cretaceous adakitic rocks in the Zhantang area of SE China interior were associated with the Late Mesozoic lithospheric extension and and basaltic underplating. Mao et al. (2004a, b) suggest that the petrogenesis of 183-158 Ma Tangquan adakitic rocks in the southwest of Fujian province has been related to lithosphere extension in SE China.

4.1.3 Syn-collisional setting

Zhang et al. (2006c) suggested that Triassic (229±7 Ma) Guanshan adakitic granites in the southeast corner of the Qilian orogenic belt were possibly generated during Triassic continental collision between the North China and the South China plates.

4.1.4 Post-collisional setting

Cenozoic adakitic rocks occurring in the Tibetan Plateau were generally later than 70-55 Ma, when India plate began to collide with Asia plate, and were considered to have been generated in post-collisional setting (Zhang et al., 2003a; Chung et al., 2003; Gao et al., 2003a, b; 2006; Hou et al., 2004a, b; Jiang et al., 2006; Ke et al., 2006; Lai, 2003; Lai et al., 2003; Liu et al., 2003; Mo et al., 2006; Qu et al., 2003, 2004a, b; Wang et al., 2005; Wei et al., 2005; Yao et al., 2006; Cai et al., 2005a).

4.2. Petrogenesis

4.2.1 Partial melting of subducted oceanic crust

Most adakites or adakitic rocks were considered to have been derived by partial melting of subducted oceanic crust (e.g., Dong and Tian, 2004; Zhang et al., 2003a, b, c; Jian et al., 2003; Li and Li, 2003, 2004; Liu et al., 2003b; Fu et al., 2005; Pei et al., 2003; Shi et al., 2003, 2005; Tao et al., 2005; Wang et al., 2003a, 2004c, 2006a, d, 2007a; Xiong et al., 2005a; Yang et al., 2005; Zhang et al., 2004a, c, 2005a, 2006a, b; Zhu et al., 2003, 2004; Niu et al., 2006). Li and Li (2003, 2004) suggested that the Xiwan (NE Jiangxi) adakitic granites were generated by low degrees of partial melting of subducted, spilitized oceanic crust at pressures high enough to stabilize garnet and amphibole. Wang et al. (2004c) suggested that the late Archean Wutai MORB-arc-back arc basalt-adakite sutes possibly originated from magma mixing between MORB-like melts and subduction (slab)-related melts, and intra-oceanic subduction, coupled with contemporary MORB-type mantle upwelling related to back arc basin extension, could account for the interaction between the two components.

Wang et al. (2003a, 2006a, 2007a) suggested that Carboniferous adakite-high-Mg andesite-Nb-enriched arc basalt and basaltic andesite （NEB） suites in the Northern Tianshan area (Xinjiang) are an example of the adakite metasomatic arc volcanic (or magmatic) series, the adakites were most probably derived by partial melting of subducting young oceanic crust of the Carboniferous Northern Tianshan Ocean, high-Mg andesites originated from interaction between mantle and slab melts and subsequent addition of a mantle component to the slab melts, and NEBs were generated by partial melting of mantle wedge peridotites likely metasomatized by slab melts and minor fluids. Zhang et al. (2006) and Han et al. (2006) considered that the early Carboniferous Tuwu-Yandong adakitic porphyries in the Northern Tianshan were derived by partial melting of a subduction-related oceanic slab. Zhang et al. (2004a, 2005a) thought that early Devonian adakite-NEB suites in north Junggar (Xinjiang) were in petrogenesis related to the southward subduction of the Paleo-Asian Ocean, the adakites were derived from the subducted Paleo-Asian oceanic crust, and the Nb-enriched basalt was originated by the partial melting of the mantle wedge slightly contaminated by the continental crust.

4.2.2 Partial melting of stalled oceanic crust

Although Cenozoic adakitic rocks in the southern and eastern Tibet were generated during post-collisional setting, they are considered to have been originated from old (pre-Cretaceous or Cretaceous) stalled oceanic crust in the mantle by some researchers. E.g., Hou et al. (2003) suggested that in Tibetan collision-orogenic belts，old (pre-Cretaceous) oceanic crustal rocks were subducted an d accumulated in mantle lithosphere， where metamophism and detachment caused their partial melting under the condition of eclogite facies and resulted in the generation of Cenozoic adakitic magmas．Gao et al. (2003a, b) thought that the Neogene adakitic porphyries in the southern Tibetan were formed by partial melting of dead subducted oceanic crust in a post-collision setting, and K-enrichment in the adakitc rocks is attributed to the interaction of slab-derived melts, i.e., adakites, with the metasomatized mantle during the ascent. Based on isotopic data of 6 copper deposits of Jiama，Lakang'e，Nanmu，Chongjiang，Tinggong and Dongga in the Gangdise copper belt, Qu et al. (2004a, b) considered that the Neogene adakitic porphyries associated with Cu mineralization were mainly derived from partial melting of the Cretaceous-Early Triassic subducted Yarlung Zangbo oceanic crust under eclogite facies condition with a minor mixing of subducted sediments in the magma source.

Taking into account that the Middle-Jurassic Dexing (NE Jiangxi) adakitic porphyries is closed to a suite of Neoproterozoic (~1000 Ma) ophiolitic mélanges and their similar Nd isotope compositions, Wang et al. (2006c) proposed that, in addition to partial melting of delaminated lower crust, the Dexing adakitic porphyries may also be derived by alternative mechanism, i.e., partial melting of the remnants of a Neoproterozoic subducted slab, stalled in the mantle.

Based on major and trace element and Nd-Sr-Pb isotope compositions, Li (2006) suggest that the early Jurassic adakitic volcanic rocks of the Xinglonggou Formation in Beipiao area of West Liaoning Province were generated by partial melting of subducted oceanic slab of the Paleo-Asian Ocean and interacted with the Archean lithosphere mantle during the ascending magmas.

4.2.3 Partial melting of thickened lower crust

Most adakitic rocks occurring extensional/contraction setting within continent and post-collisional setting were considered to have been derived by partial melting of thickened lower crust (e.g., Zhang et al., 2003a, b, 2004d,e, f; Cai et al., 2003, 2004, 2005b; Castillo, 2006; Chung et al., 2003; Davis, 2003; Guo et al., 2006; Hou et al., 2004a; Ke et al., 2005; Lai, 2003; Lai et al., 2003; Liu et al., 2003; Ma et al., 2004; Ma et al., 2004a, b, 2006; Qin et al., 2005; Wang et al., 2003d, e, 2005b,2006f, 2007b, c; Wei et al., 2005; Xu and Wang, 2003; Xue et al., 2006; Zhai, 2004; Zhang et al., 2006d; Zhao et al., 2004a, b, 2006; Zhu et al., 2003; Xiao et al., 2004). Especially, for those Cenozoic adakitic rocks in the southern Tibet were also considered to have been derived by partial melting of eclogitic lower crust (Zhang et al., 2003a; Chung et al., 2003; Hou et al., 2004a). Additionally, some adakitic rocks occurring arc setting were considered to have been generated by lower crust thickened by arc-continent collision or basaltic magma underplating (e.g., Jin et al., 2005; Liu et al., 2003c; Yuan et al., 2003).

4.2.4 Partial melting of delaminated or foundering lower crust

Xu et al. (2002) proposed that partial melting of lower crust delaminated into the below lithospheric mantle could generated early Cretaceous adakitic magmas in the Ningzhen area, eastern Yangtze Block. Gao et al. (2004) suggested that the the Late Jurassic high Mg andesite-adakitic rock suites in the Xinglonggou area, Northern China Block, derived from ancient mafic lower crust that foundered into the convecting mantle and subsequently melted and interacted with peridotite. Xiao et al. (2004), Wang et al. (2006f) and Xu et al. (2006a, b) also considered that some high-Mg andesites or adakites were generated by partial melting of delaminated lower crust. Wang et al. (2004d, e, 2006b, c, 2007b) suggested that some Jurassic-Cretaceous adakitic rocks in the eastern Yangtze Block were derived from eclogitic lower crust delaminated or foundering into the underlying hotter and more plastic lithosphere or the asthenospheric mantle.

4.2.5 Magmatic mixing

Wang et al. (2003b) reported that some Late Mesozoic intermediate-acid intrusive rocks in the Tongling area, eastern Yangtze Block exhibited most elemental geochemical characteristics similar to an adakite, such as high Na_2O, Al_2O_3, and Sr contents and high Sr/Y and La/Yb ratios, but they had isotopic compositions much different from an adakite, such as lowεNd(t) (-9.16~-16.55) and high $(^{87}Sr/^{86}Sr)_i$(0.7068~0.7105), as well as some of them show relatively higher Y and Yb contents than those of an adakite. Wang et al. (2003b) proposed that the Tongling intrusive rocks were most probably produced by the mixing of mantle-derived basaltic magma and adakite-like magma derived from the melting of basaltic lower crust that was heated by the mantle-derived shoshonitic magmas.

4.2.6 Melting of enriched lithospheric mantle

Jiang et al. (2006) suggested that the Yulong monzogranite-porphyry in the eastern Tibet (China) had some affinities with the adakite (e.g., high SiO_2 and Al_2O_3, and low MgO contents, depleted in Y and Yb, and enrichment in Sr with high Sr / Y and La / Yb ratios, and no Eu anomalies), and were directly derived by partial melting of an enriched lithospheric mantle. Recently, Gao et al. (2007) considered that the southern Tibetan Neogene adakitic rocks were derived from an upper mantle source metasomatised by slab-derived melts.

4.2.7 Crustal assimilation and fractional crystallization (AFC) or fractional crystallization (FC)

Wang Y. et al. (2004b) considered that Cretaceous adakitic rocks in the Lower Reaches of Yangtze River (eastern China) were derived from AFC process involving basalts. Li et al. (2006) suggested that the Late Jurassic-Early Cretaceous adakitic rocks were generated by FC process of enriched mantle-derived magmas.

4.4 Experimental Constraints on the Petrogenesis

Some researchers summarized previous experimental data in order to constraint the petrogenesis of adakitic rocks in China (e.g., Wang et al., 2003e; Xu and Ma, 2003). Wang et al.

(2003e) proposed that high K_2O contents (relative to slab-derived adakites) of some adakitic rocks in China are likely related to high pressure (1.5-4.0 GPa) melting or high K_2O contents of metabasalts or eclogites. Based the summarization regarding previous experimental studies on the dehydration melting of metabasalt, Xu and Ma (2003) proposed that the key factors controlling the composition of adakitic rocks were starting materials，water contents，and thermal structure of lithosphere. They considered that the Mesozoic K-rich adakitic granitoid magma in eastern China was possibly generated by partial melting of underplated alkali-rich basalt，at pressures between 1.0 GPa and 1.5 GPa and temperatures from 850 to 1080℃ in a special setting where the crust was switched from compression to extension, leaving pyroxenite residue.

Xiong et al. (2005b, 2006b) designed synthesis melting experiments on a natural basalt (with 2 or 5 wt.% H_2O added) at 1.0-2.5 GPa and 900-1100°C in order to investigate the stability field of rutile and rutile/liquid HFSE partitioning during partial melting of hydrous basalt. Their experiments found that rutile occurred in the partial melting field of hydrated basalt at pressures higher than approximate 1.5 GPa, depending on H_2O content and bulk composition (especially TiO_2 and K_2O), and demonstrated that both D_{Nb} and D_{Ta} decreased with increasing H_2O content but increased with decreasing temperature. Xiong et al. (2005b) considered that rutile was a necessary residual phase during the generation of Archean tonalite-trondhjemite-granodiorite (TTG) magmas to account for the negative Nb-Ta anomaly of the magmas, and the depth for TTG production via melting of subducted oceanic crust had to be more than 45-50 km based on the approximate 1.5 GPa minimum pressure for rutile appearance.

Xiong et al. (2006a) also noted that Cenozoic adakites had Na_2O contents below 5.8 wt% with ~95% samples lower than 5.0 wt%, and were generally depleted in this component relative to experimental basalt partial melts (mostly beyond 5.0 wt.% and up to 9.0 wt.% Na_2O) produced under 1.5–3.0 GPa conditions that were most relevant to adakite production. They interpreted the adakite Na depletion to be also a consequence of the melt / rock reaction that took place within the hot mantle wedge. During ascent and reaction with mantle peridotite, primary adakite melts gained mantle components MgO, CaO, Cr and Ni but lost Na_2O, SiO_2 and perhaps K_2O to the mantle, leading to Na-rich mantle metasomatism. Phase relationships in the reaction system siliceous melt + peridotite and quantitative calculation suggested that assimilation of mantle clinopyroxene, olivine and spinel and fractional crystallization of sodic amphibole and orthopyroxene, under conditions of moderate T/P and increasing melt mass, was an important process that modified the composition of adakites and causes the Na depletion.

V. METAL MINERALIZATION RELATED TO ADAKITES OR ADAKITIC ROCKS AND THEIR ASSOCIATED ROCK SUITES

5.1 The Spatial Distribution of Metal Mineralization Related to Adakites or Adakitic Rocks

Recently, many researchers reported Cu- Au mineralization related to adakites or adakitic rocks in China (Wang et al., 2001a, b, 2003c, e, 2004b, e, f, 2006a, b, c, d, 2007b; Zhang, 2003; Zhang et al. 2003a, b, c, 2004c, 2006a, b, h, e; Hou et al., 2003, 2004a, b, e, f, 2005; Zhao et al., 2004a; Zhu et al., 2004; Liu et al., 2004; Huang et al., 2005; Cai et al., 2005a; Fu et al., 2005; Wu et al., 2005; Xiong et al., 2005a; Yang et al., 2005; Luo, 2006; Ma et al., 2004; Mo et al., 2006; Qu et al., 2003, 2004a, b; Rui et al., 2006; Wan and Zhang, 2006; Zeng et al., 2006). Zhang et al. (2004e, f) systemically summarizes the distribution of the Au, Cu and Ag deposits associated with adakites or adakitic rocks in China. They considered that these deposits could be divided into two major types: occurring in orogenic belts and within continental blocks，as well as several mineralization belts or sub-belts. The deposits in orogenic belts distribute in the Paleo-Asian Oceanic metallogenetic belt, Qinling-Qilianshan-Kunlun metallogenetic belt, Circum-Pacific metallogenetic belt and Neo-Tethys metallogenetic belt. However, the deposits within continental blocks distribute in East China metallogenetic belt, Qinghai-Tibet Plateau metallogenetic belt and southeastern Tibet-southwest Sichuan-northwest Yunnan meta11ogenetic belt (Zhang et al., 2004e, f).

5.2 Adakites or Adakitic Rock Constraints on Metallogenesis

Zhang et al. (2004f) consider that the key factor which caused Cu-Au mineralization associated with adakites was the dehydration during the transformation from an amphibolite to an eclogite, which favored to generate adakitic magmas and exact the metal elements enriched in the mantle and basic rocks into magmas.

Liu et al. (2004) reviewed Cu-Au metallogenesis associated with adakites or adakitic rocks, and considered that adakites or adakitic rocks and their clan (such as high magnesian andesites, magnesian andesite, Niobium—enriched basalts，and high Niobium basalts，etc) were the host rocks of most porphyry copper deposits, and the source rocks of many epithermal Au systems. They suggested that the genetic relationship between them might stem from the inherent natures of adakitic magmas with suficient fluids, high oxygen fugacity and mafic source region，which were preferred for Cu，Au and other deeply sourced metals to be extracted and enriched, and finally economically mineralized.

Hou et al. (2005) suggested that the Gangdese 13.6-16.9 Ma porphyry Cu-Mo system associated coeval (14.5 -17.6 Ma) adakitic porphyries in southern Tibet was generated during the post-collision crustal extension, partial melting of a thickened lower crust beneath southern Tibet involved input of materia1s derived from the depleted mantle, which provided necessary heat and metals (Cu, Au) for the generation of Cu-bearing adakitic melts, and the transition of residual phase from amphibole-bearing to garnet-bearing assemblages in the garnet amphibolite source during melting was the fundamental and important process for the formation of the fertile adakite and porphyry Cu systems in southern Tibet. However, these porphyry Cu deposits were also considered to have been related to partial melting of the subducted Yarlung Zangbo oceanic crust under eclogite facies condition with a minor mixing of subducted sediments in the magma source (Qu et al., 2003, 2004a, b) or an upper mantle source metasomatised by slab-derived melts (Gao et al., 2007).

Rui et al. (2006) suggest that participation of oceanic crust- or upper mantle-derived material is essential for porphyry copper deposits which are formed by pre -collisional B-type subduction and post-collisional A-type subduction, and copper -bearing porphyries and adakites probably result from subduction and metasomatism.

Wang et al. (2001a, b) found that the Cu-Au mineralization in the eastern Yangtze Block is associated with Late Mesozoic adakitic rocks. Lately, Wang et al. (2003c, e, 2004b, e, f, 2006a, b, c, d, 2007b) summarized the relation between Cu-Au mineralization and adakitic rocks in the eastern Yangtze Block. Wang et al. (2004b, e, 2006a, b, c, d, 2007b) found that field relations, isotope systematics, and plate tectonic reconstructions require that felsic adakites in the Yangtze Block and the Dabie Orogen, eastern China were not derived from a subducting slab, despite the signature of a mantle component in the contemporaneous mafic adakite hosts of Cu-Au deposits in the same areas. The apparently contradictory requirements are accounted for by a) a deep crustal melting origin for barren adakites and b) a crustal delamination origin, followed by ascent through lithospheric mantle, for adakites associated with mineralization. The crustal delamination process associated with the prospective porphyries duplicates the metallogenically essential aspects of the subduction environment. The importance of adakitic magmas in the genesis of porphyry-style Cu-Au deposits is affirmed by these findings, but the range of prospective tectonic environments is extended to include an important, intra-plate, post-subduction setting. The porphyries of eastern China demonstrate a previously unrecognized relationship between one particular tectonic environment and porphyry-style mineralization that may occur elsewhere.

Except Cu mineralization associated with Permian adakitic rocks in the Awulale area (Zhao et al., 2004a, 2006), most Cu-Au mineralization associated with Paleozoic adakitic rocks in the northern Xinjiang area were considered to have been related to partial melting of subducted oceanic crust (e.g., Wang et al., 2003e, 2006a, 2007a; Xiong et al., 2005a; Wan and Zhang, 2006; Yang et al., 2005; Zhang et al., 2004c, 2006a, b, h). Wang et al. (2006a) reported that copper (gold) deposits (e.g., Dabate, Axi, Tuwu-Yandong, Chihu, etc) are associated with Carboniferous adakite-high-Mg andesite-Nb-enriched arc basalts and basaltic andesite (NEB) suites occur in the Northern Tianshan Range (Xinjiang). They considered that the copper (gold) mineralization in this area were most probably related to the interaction between subducted young oceanic crust-derived adakitic melts and mantle wedge peridotites. Owing to their high oxygen fugacity (fO_2), the interaction of slab-derived adakitic magmas with mantle wedge peridotites may have caused decomposition of metal sulfides, thereby allowing Cu (or Au) to enter the magmas. This process may represent the fundamental reason why Cu (or Au) mineralization is closely associated with many adakites, high-Mg andesites and NEBs in the Northern Tianshan Range (Wang et al., 2006a).

VI. SOME GEODYNAMIC INFERENCES FROM ADAKITIC ROCKS

6.1 Adakites, Subduction, Underplating and Crustal Growth

Based on similar Nd-Sr isotope composition of carboniferous adakites and approximately contemporaneous ophiolites in the Bayingou area, Northern Tianshan Range., Wang et al. (2006a, 2007a) considered that the adakites were most probably derived by partial melting of subducting young oceanic crust of the Carboniferous Northern Tianshan Ocean. Therefore, in the Carboniferous, the Northern Tianshan Range was in an arc rather than continental rift setting, lateral rather than vertical accretion processes must have dominated crustal growth in the Tianshan Range, and partial melting of subducting oceanic crust played an important role in this crustal growth along with the depleted upper mantle. Zhang et al. (2004a, 2005a) suggested that the distribution of the the adakite-Nb-enriched basalt suites in early Devonian Group in north Junggar (northern Xinjiang) indicated that the Palaeo-Asian oceanic crust subducted southwards beneath the Kazakhstan-Junggar Plate in Early Devonian.

Zhao et al. (2006) considered that both subducted oceanic slab-related adakites and underplating basalt-related adakites were generated in Late Paleozoic in the Northern Xinjiang. Based on the distribution of two types of adakites and the close association of the first type of adakites with high-Mg andesites, Nb-enriched basalts and picritic rocks, Zhao et al. (2006) deduced that the crustal growth in north Xinjiang had multi-fashions. The growth direction included both vertical and horizontal accretion, the tectonic process involved the oblique subduction of oceanic slab, slab tear, slab window, subduction erosion and the underplating of basaltic materials, and the growth materials contained subducted oceanic slab, mantle wedge, forearc prism, mantle wedge modified by adakitic melt, and adakitic melt contaminated by the manle wedge and upwelling asthenospheric mantle.

Li and Li (2003, 2004) suggested that the SHRIMP U-Pb zircon age of 968±23 Ma for the subducted oceanic crust-derived Xiwan (NE Jiangxi) adakitic granites should re-interpreted as the timing of subduction of oceanic crust, rather than as the age of oceanic crustal formation as previously interpreted.

6.2 Adakitic Rocks and Delamination or Foundering of Thickened Lower Crust

Owing to adakitic magmas originating from eclogitic source, some researchers started to give their attention to the relationship between the adakitic rocks and derlamination or foundering of thick lower crust during 2001-2002 (Wang et al., 2001 a, b, c; Zhang et al., 2001a, b; Qian, 2001; Xu et al., 2002). Based on lots of research, their relationship may be summarized in two parts: (1) adakitic magmas extraction from the residual eclogitic source is a prerequisite for lower crustal delamination or foundering (Wang et al., 2001 a, b, c, 2007b; Zhang et al., 2001a, b, 2005b, 2006g; Qian, 2001); (2) lower crustal delamination or foundering into underlying mantle is a prerequisite for adakitic magmas (Xu et al., 2002, 2006a, b; Gao et al., 2004; Wang et al., 2003e, 2004d, e, 2006b, c).

6.3 Adakitic Rocks and Plateau

Experimental data suggested that the depth for adakitic magma production via melting of lower crust must be more than 40-50 km (e.g., Rapp et al., 1991; Rapp and Watson, 1995; Xiong et al., 2005b). Based on the genesis of adakites, as well as other geological evidences，Zhang et al. (2001b) proposed that in Mid-Late Yanshanian period the eastern part of China continent was probably a plateau， which was uplifted in Mid-Late Jurassic and thinned after Early Cretaceous, the uplifting and thinning of the plateau were due to intra-continental orogenic events and delamination of lower continental crust, respectively. Recently, Zhang et al. (2005b, 2007) further constraint approximately boundary of the East China Plateau during late Mesozoic Era in terms of newly found adakitic rocks derived by thickened lower crust.

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ORIGIN OF THE POSTCOLLISIONAL ULTRAPOTASSIC ROCKS IN LHASA BLOCK, TIBET: A REVIEW

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Abstract: The ultrapotassic rock is a special type of rock classified by their geochemical definition (K_2O/Na_2O >2, K_2O>3%, and MgO>3%). This paper reviews the spatial and temporal distribution, petrology, elemental and isotopic geochemistry, origin and tectonic implications of the postcollisional ultrapotassic rocks and related potassic rock in the Lhasa Block, Tibetan Plateau. The rocks in the Lhasa Block are tectonically linked to N-S normal fault system. The age of ultra-potassic rocks ranges from 12 Ma to 28 Ma, slightly earlier than the potassic rocks (9-24 Ma). The rock types are mainly trachyte, trachyandesite, basaltic trachyandesite, phonolite and tephriphonolite. They have high LREE and LILE concentration, and low HFSE. Their continent-like isotope characteristics (extremely high Sr and Pb and low Nd isotopes) show the affinity of the Himalaya basement, implying that the subduction of the India plate beneath the Lhasa block and contaminated mantle source region of the magmatic rocks. Break-off or delamination of the subducted oceanic/continental materials may have played an essential role in the genesis of the ultrapotassic rocks in the Lhasa Block.

I. INTRODUCTION

The Tibetan plateau created by the India-Asian collision around ~65 Ma ago is the largest (covering more than 550000 km^2 and more than 82% of the world's land higher than 4000 m), youngest (the Indian continent is still moving northward) and the highest (average altitude of 5023 m) orogen in the world [1], It is one of the most important natural lab for studying the young and ongoing orogenic belt on the earth. The postcollisional magmatism on the plateau after the India-Asian collision are the record that is pivotal for revealing the plateau's uplift, northward subduction of Indian plate, and the evolution of the deep lithosphere [2, 3]. Among the tectonic units, the Lhasa Block in southern Tibet is the frontiers that face the collision and underthrust of India continent. The ultrapotassic rocks found and studied in the past 10 year, with the age varying between 28 Ma and 11 Ma, is one of the most important object to understand the postcollisional processes in the period. The detailed studies involving geochronology, petrology and geochemistry allowed us to construct the petrogenesis model of the rocks and to evaluate the nature of their source region, and to establish the possible relationship between magmatism and the processes of the India-Asia subduction. This review summarizes the main characteristics of the ultrapotassic rocks in western Lhasa Block. We start with the age and geochemistry aspects, then focus on the potential implication of these rocks on the lithospheric structure of the continental subduction in Tibet.

II. ULTRAPOTASIC ROCKS IN THE WORLD: DEFINITION AND GEOCHEMISTRY

The definition of "ultrapotassic rocks" introduced by Foley et al [4] is mainly according to their whole rock chemistry other than mineralolgy. The ultrapotassic rocks (K_2O/Na_2O >2, K_2O>3%, and MgO>3%) can be further divided into three groups (Lamproites, kamafugites and the rocks occur in orogenic areas). The most significant feature in mineralogy of the ultrapotassic rocks is that, their phenocrysts contain not only olivine, but also the K-rich minerals, such as lecucite and phlogopite. In the diagram of total alkaline versus silicon (TAS), the ultrapotassic rocks plotted in the middle-upper part, covering the fields of trachybasalt, basaltic trachyandesite, trachyandesite, trachyte (trachydacite) and phonotephrite, tephriphonolite, phonolite, etc. In the following discussion, ultrapotassic rock (abbreviate as ultra-K rocks) referred to the above definition and related potassic rocks, and will focus on the third group of rocks (orogenic ultra-K). The ultra-K rocks gained much attention since their special geochemical characteristics and their close relationship with large or super-large scale Cu, Au deposits. A special volume of the ultra-K research were published on *Lithos* in 1992 (vol 28), and the book named **"***Potassic Igneous Rocks and Associated Gold-Copper Mineralization***"** have been published for three editions (Müller and Groves, 1995, 1997, 2000) [5]. The rocks could occur from Precambrian to present through the geological history [6, 7]. The youngest potassic and ultra-K rocks (<60 Ma) could be found in 5 tectonic settings, including continental arc, postcollisional arc, initial oceanic arc, late oceanic arc, and within-plate settings. In these five environments, except for the within-plate settings in which there is not any significant subduction-related event in the near history, the other five types are all closely have the affinity of subduction processes. The most wide spreading type is the continental arc setting, which can be typically found in the Andean volcanic belt and in the Aeolian Islands in the Mediterranean areas, Roman Province and north American Cordillera. The typical postcollisional arcs are in Alps and Iran, well-known as young orogenic belt between continent collisions [5]. The ultrapotassic magmatism in the southern Tibet must have taken place in a postcollisional arc tectonic setting, just totally after the subduction of the Tethyan oceanic crust and the collision between India and Asia [8].

The ultra-potassic rocks also have distinctive geochemical features in correlation with the above- mentioned classification based on major element composition. They are enriched in light REE (LREE) and Rb, Cs, Ba, Th (LILE), showing HFSE negative anomaly of Ti, Nb, and Ta, etc. They have high Sr and low Nd composition and enriched radiogenic Pb, indicating that they originated from an enriched upper mantle (EMI or EMII). This implies that the continental materials have contaminated the source region and recycled through the magmatism [9-16]. We must keep two things in mind in petrogenetic evaluation, one is that the rocks showing mantle-origin feature (such as high $Mg^{\#}$ and Ni and Cr contents), meanwhile they also show crustal-origin nature (enriched in HREE and LILE, depleted in HFSE, with high Sr and low Nd isotopic values). Some models have been proposed for explaining the "mantle-crust" two-face origin, such as high-degree source-region contamination of crustal materials; zone refining mechanism of a large volume of the mantle; partial melting of a pre-enriched phlogopite-bearing mantle peridotite; and the K-rich magma from a H_2O- and K_2O-rich high pressure clinopyroxene. Among them, the most acceptable model is the partial melting of a pre-enriched mantle source-region [4, 17-18]. As a whole for the genesis of the ultrapotassic rocks, although the degree of partial melting, way of mantle metasomatism, and where the enrichment processes happen, are still unclear. The concept that the rocks are indicative of a deep subduction of continental or oceanic material is commonly accepted by many researchers [19]. There are still some remaining questions, such as how the continental agent recycle to deep mantle and release the K- and CO_2-rich fluid, when and how did the continental materials metasomatized the mantle happen, are still in debate.

III. ULTRAPOTASSIC ROCKS IN TIBET: PREVIOUS WORK AND GENERAL

FEATURES

3.1 Previous research

The ultrapotassic magmatism is widely distributed in the hinterland and adjacent areas of Tibetan plateau after India collided with Asia. Since the 1980's, some progresses concerning the age, petrology, and geochemistry of the rocks in Qiangtang block, Hoh Xil, and Kunlun in northern plateau and the eastern margin were achieved [20-29]. But the reports of ultrapotassic rocks in southern Tibet were still few and only limited to some localities before 1999 [20-23, 30].

The research of ultrapotassic rocks in western Lhasa block getting more and more progresses by finding new localities and accumulating new high-quality geochemical data since 1999 represented by the paper of Miller et al [31]. The potassic and typical ultra-K rocks were found in Shiquanhe, Xungba, Bangba areas [31-32], Wuyu basin and Yangying geothermal field [33-36]、Dajiacuo and Pabbai Zong [37], Bugasi of the east bank of Zabuye salt lake, Zebujiabuza and Dela areas [38-40], and the Dangreyongcuo-Xurucuo north-south trending graben [40-42]. Our research, started in 1998, have got some results on Ar-Ar dating and geochemistry on the rocks from east bank of Zabuye salt lake, Gongmutang.in Zhognba county, Dangreyongcuo and Xurucuo areas [8, 38, 42-45].

3.2 General features

The main features of the potassic and ultrapotassic rocks in the Lhasa block are as follows [31-32, 36-46]: (1) They have close relation to the N-S normal fault system (or called the N-S rifts, graben or the west-east extensional tectonics), north-south prolongation lakes (Zabuye salt lake, Dangreyongcuo and Xurucuo), or the Cenozoic basins (Wuyu basin, Sailipu basin). (2) The ultrapotassic rocks are distributed in the areas to the west of 87°E, while the potassic rocks are located from Shiquanhe to Lhasa, not limited by the 87°E line. (3) The age of ultrapotassic rocks range from 12 Ma to 28 Ma, sounds earlier than the shoshonitic rocks (9-24 Ma). The ultrapotassic rocks exhibit an eastward trending of changing younger. (4) The rock types are mainly trachyte, trachyandesite, basaltic trachyandesite, phonolite and tephriphonolite. (5) The rocks are wildly enriched in LREE and LILE, depleted in HFSE. They have extremely high Sr and Pb and low Nd isotopes, showing the affinity of the Himalayan basement. This maybe implies the subduction of India plate beneath Lhasa block that contributed to the source region of the rocks. (6) The age and scale of the potassic and ultrapotassic magmatism are ignored in the past models for illustrating the evolution of the plateau. In contrast, the scale of the Linzizong volcanics were over-estimated in Lhasa block, since the ultra-K rocks are mostly found and separated from Linzizong group by detailed dating. The ultra-K rocks will play very important role in revealing the postcollisional processes in southern Tibet and in tracing the subduction of India plate underneath Asia along the Yalung Zangpo suture zone.

IV. SPATIAL AND TEMPORAL DISTRIBUTION OF THE ULTRA-K ROCKS IN LHASA BLOCK

Published age data of the potassic and ultrapotassic rock in the Lhasa block are listed in Table 1 and plotted in Fig 1 along with their localities. Although the postcollisional potassic and ultrapotassic rocks found in the Lhasa block are not so large in volumes, but their occurrences are enough to change our former understanding of the distributions of the postcollisional rocks in southern Tibet on the plateau. This type of rocks has been regarded occurring only in Qiangtang, Hoh Xil and West Kunlun, and being very limited in the Lhasa Block. But now we could see that the rocks have been widely found in Lhasa block, from Shiquanhe and Xungba-Bangba area in the far west (more than 2000 km^2) [22, 31], to the east bank of Zabuye salt lake (>400 km^2) [36, 38-39], to Dangreyongcuo and Xurucuo (~150 km^2) [40-42], to the Pabbai Zong ultra-K dikes near Shigaze [37], and to the central part around Wuyu basin and Yangying geothermal field [34-35], etc. The postcollisional rocks show a widely distribution in such a 1000-km long west-east space in Lhasa block. In the future research, more potential new localities could be found in Lhasa block based on detailed dating and mapping work are prospected.

Table 1 Summary of published dating results of potassic and ultrapotassic rocks in Lhasa block, southern Tibet

(after Zhao et al., 2006) [42]

No.	Locality	Rock	Method	Mineral/Whole rock	Age (Ma)	Sample No.	Data source
[1]	Shiquanhe	trachyte, rhyolite	Ar-Ar	minerals	16-20	3	Turner et al., 1996, [22]
[1]	Shiquanhe	trachyandesite	Ar-Ar	phlogopite	21.2-24	3	Williams et al., 2004 [32]
[2]	Xungba-Bangba	potassic & ultra-K	Ar-Ar,	Minerals & whole	18-25	6	Miller et al., 1999 [31]

			Rb-Sr	rock			
[3]	Xungba-Bangba	Calc-alcline	Ar-Ar, Rb-Sr	Minerals & whole rock	16-17	11	Miller et al., 1999 [31]
[4]	Zhabuye	trachyandesite	Ar-Ar	Sanidine & biotite	16.07-16.23	6	Nomade et al., 2004 [36]
[4]	Bugasi	ultra-K，trachyandesite	K-Ar	whole rock	15.8-15.9	2	Ma et al., 2002 [38]
[4]	Bugasi	ultra-K，trachyandesite	Ar-Ar	whole rock	15.53	1	Chen et al. 2006 [39]
[5]	Gongmutang, Zhongba	ultra-K	Ar-Ar	whole rock	16.3-16.5	2	Mo et al, 2006 [45]
[6]	Dajiacuo, Angren	dacite	Ar-Ar	Amphinolite & whole rock	17-19	2	Williams et al., 2001 [37]
[7]	Pabbai Zong	ultra-K	Ar-Ar	phlogopite	13-18	4	Williams et al., 2001[37]
[8]	Xurucuo	trachyte	Ar-Ar	phlogopite	11.2	1	Zhao et al., 2006[42]
[9]	Chazi	trachyte，trachyandesite	Ar-Ar	phlogopite	8.2-13.3	3	Ding et al., 2003 [41]
[10]	Dangreyongcuo, Nima	trachyte	Ar-Ar	Phlogopite & sanidine	13.0-13.7	4	Zhao et al., 2006[42]
[10]	Dangreyongcuo, Nima	ultra-K，leucite phonolite	K-Ar	whole rock	12.6	1	Liao et al., 2002[40]
[11]	Wnebu	Trachyte & phonolite	Ar-Ar	sanidine	23	2	Ding et al., 2003 [41]
[12]	Nanmulin	dacite	Ar-Ar	Sanidine & phlogopite	14.03-15.10	4	Spicer et al., 2003 [46]
[13]	Wuyu basin, Nanmulin	trachyte，trachyandesite, etc	Ar-Ar	Sanidine & biotite	12.00-13.63	5	Zhou et al., 2002[35]
[13]	Wuyu basin, Nanmulin	Granite porphyry	Ar-Ar	sanidine	10.84	1	Zhou et al., 2002[35]
[14]	Majiang, Nimu	Andesite & trachyte	Ar-Ar	Sanidine, Plagioclase, etc	10.1-15.8	5	Coulon et al., 1986[21]
[15]	Yangying, Dangxiong	rhyolite	Ar-Ar	Sanidine & biotite	10.65-10.92	3	Nomade et al., 2004 [36]
[15]	Yangying, Dangxiong	trachyte，rhyolite	K-Ar	whole rock	9.05-10.83	6	Nomade et al., 2004 [36]

From Table 1 and Fig.1, one could conclude that the age of the ultrapotassic magmatism change from 18-25 Ma in Shiquanhe, Xungba and Bangba region, to 12-16 Ma in Zabuye and Dangreyongcuo regions of, and then to 10-16 Ma in Majiang, Wuyu and Yangying areas of Shigaze and Lhasa regions in central Lhasa block. In a 1000-km distance, the age of the magmatism sounds show eastward decrease in age, yielding the difference of ~8 Ma. From present research, the ultra-K rocks occur from Shiquanhe to 87°E. In contrast to the Gangdese batholith that showing clear west-east trending distribution parallel to the suture zone in southern Lhasa blockl, the potassic and ultra-K rocks show less feature that parallel to the suture. They could scatter in the southern part near the Yalung Zangpo suture, and also in the northern part close to the Bangong lake-Nujiang suture zone. In geological settings as mentioned above, the rocks show strong relationships with the young W-E extension structures (shown in Fig. 1). The time span overlap between the magmatism and the extensional systems (Fig. 2) imply that they should have origin relationship in the tectonic evolution processes on the plateau.

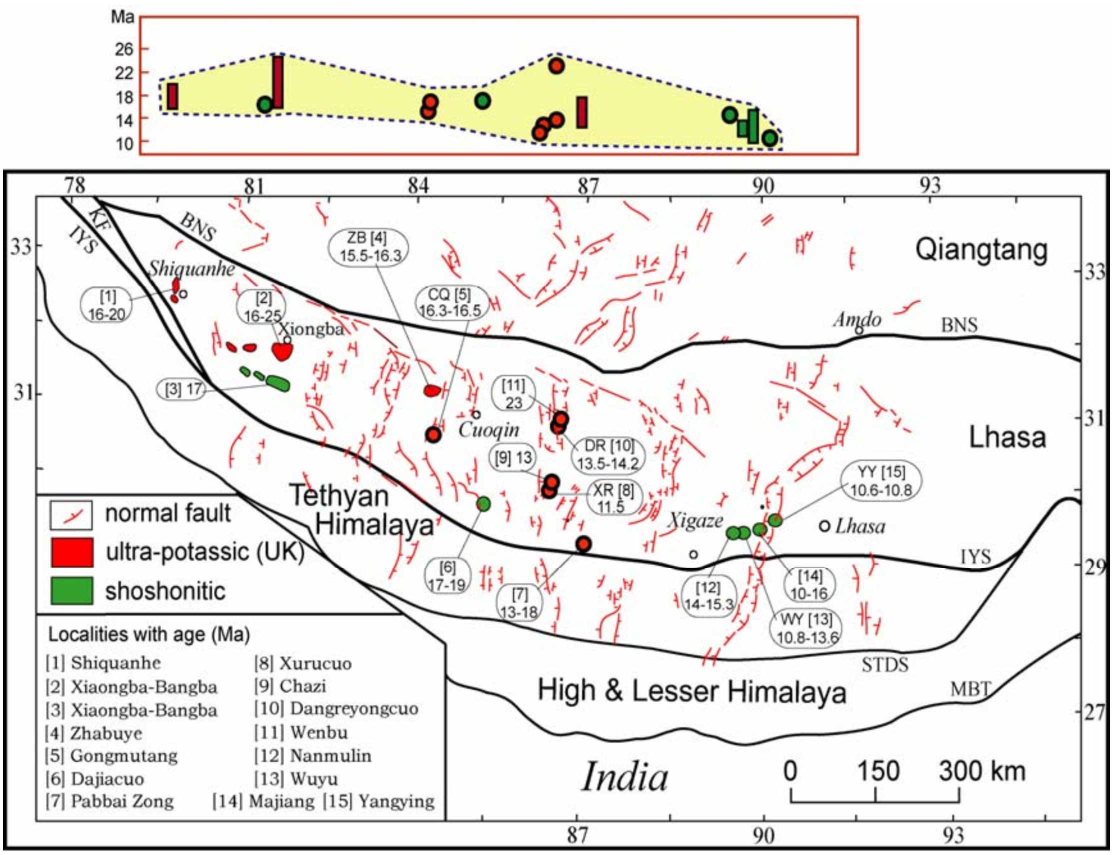

Fig. 1 Distribution of the post-collisional potassic and ultrapotassic volcanics in the Lhasa Block, southern Tibet (Modified from Zhao et al., 2006) [42]. MBT-Main boundary thrust, IYS-Indus-Yalung Zangpo suture, BNS-Bangong Lake-Nujiang suture, ATF-Altyn Tagh fault. N-S trending normal faults after Blisniuk et al.,

2001 [47]. See Table 1 for data sources, locality, age, and No. of the rocks.

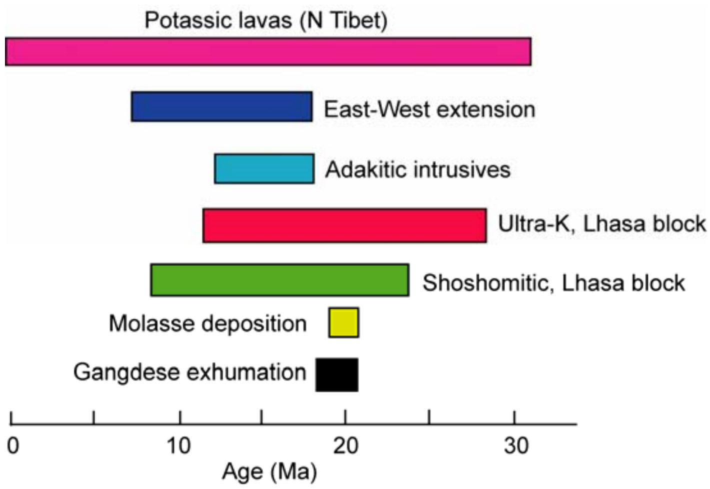

Fig 2 Age span of the Cenozoic magmatism and tectonic events in the Lhasa Block and adjacent areas. (After Zhao et al., 2006) [42].

V. POSSIBLE RELATIONSHIP BETWEEN THE ULTRAPOTASSIC ROCKS IN LHASA BLOCK AND NORTHERN TIBET

The similar ultrapotassic rocks are also reported in Qiangtang belt in northern Tibet. The ultrapotassic magmatism in Yulinshan formation in Gaize dated in the ranges of 18-30 Ma [28-29], 23-28 Ma[48], which close to that in Shiquanhe and Xungba regions (18-25 Ma) [22, 31-32] and the ultra-K magmatism in Bugasi alkali syenite, Zabuye and Wenbu (16-23 Ma) [36, 38, 41, 49]. The same type of magmatism took place in the same period in two joint belts, suggests that they should have the same or similar origin, tectonic environment and source region. The same situation is also found in the N-S trending normal faults system, which developed both in northern and southern Tibet [50]. This also indicate that Bangong lake-Nujiang suture zone, the present boundary between Qiangtang and Lhasa block, is not a giant gap in separating the two tectonic units after Lhasa collided with Qiangtang.

VI. ULTRA-K ROCKS: ORIGIN MODEL AND IMPLICATION FOR THE EVOLUTION OF TIBETAN PLATEAU

Postcollisional potassic and ultrapotaasic rocks in the Lhasa Block provide valuable opportunities for studying the petrology, geochemistry and petrogenesis of the rocks, and then revealing the deep lithospheric processes, structure and the subduction of India plate beneath

Asia [8]. As mentioned above, the potassic and ultrapotassic rocks in the Lhasa block are tectonically linked to the N-S normal faults system. There is a general consensus about an orogen's evolution, firstly the crust/lithosphere will get thicker after the collision of two continents (India and Asia), the orogen will then uplift in topography and achieve their highest altitude, and finally the orogen will collapse possibly caused by a delamination or thinning of the deep lithospheric root. In Tibet, the N-S normal faults (or E-W extensional structure) are considered to be an indicator for the late orogenic collapse caused by gravity after the plateau has uplifted to the highest altitude (Molnar and Tapponnier, 1978) [51] or for the high-speed uplift due to the lithospheric mantle thinning processes [52]. Especially in the latter model, the potassic and ultrapotassic rocks are not only regarded to be the evidence of mantle delamination, but also indicate the timing when the plateau achieved their highest elevation, and onset of the Asian monsoon and global climate changing [24, 32, 37]. If this model actually works in Tibet, we could infer that the plateau have gained its highest elevation before 25 Ma, because the ultrapotassic magmatism took place in Lhasa block 25 Ma ago. But some other people dispute that these normal faults in the N-S graben do not relate to the plateau uplift. McCaffery and Nabelek (1998) [53] proposed a block model of oblique convergence and applied it to Tibet, and concluded that the normal faults in the Himalayas and southern Tibet are not proxies for the uplift history of Tibet, they are resulted by the basal drag from the underthrusting Indian lithosphere extends northward beneath most of southern Tibet. Yin et al [50] did field mapping and emphasized that northeast-striking active faults in northern Tibet have significant left-slip components, the broad similarities in the magnitude of slip and the direction of extension for normal faults in both northern and southern Tibet imply that the entire plateau has been extending and requires an large scale regional regime of the whole east Asia. Therefore, whether the postcollisional magmatism is related to the extension tectonics or not, is still an open question. We prefer to the reality that the postcollisional magmatism span the same range of the normal faulting, dike and adakitic rocks intrusion, and a series of tectonic and magmatism events (Fig. 2). This multi-event coincidence implies that all of them should cause by a united deep lithospheric process: delamination of the lithospheric mantle in Tibet.

The postcollisional magmatism generated from the deep lithosphere is a response to the continental subduction and uplifting processes [2-3], so all the origin model of the potassic and ultra-K rocks have take the evolution of the plateau into account. There are two types of models in illustrating the rock genesis. One type is based on the research in north Tibet, it emphasized that the potassic and ultra magmatism is attributed to convective removal of the root of a previous thickened lithospheric mantle [20, 22-24, 28, 41, 54], the models focus more to the intra-continental tectonic settings without any subduction processes. The second type of model is so-called break-off/delamination model that obviously ascribe the rock origin to the subducted Tethyan oceanic crust, although the time of break-off are varied in regional scale proposed by different researchers. Harrison et al. supposed the uplift started from in ~8 Ma ago is caused by delamination of lithospheric mantle [55]. Zhong and Ding put the delamination time at 5~3 Ma and it then caused the sudden uplifting of the plateau since 3 Ma [56]. Miller et al. noted that both of the above models could work, and the essential is that a mechanism should appear to make the asthenospheric upwelling [31]. In southern Tibet, the ultra;K rocks Pabbai Zong in to the west of Shigaze are linked to subcontinental lithospheric mantle thinning [37], Mahéo et al proposed that the Neogene magmatic and metamorphic evolution of the South Asian margin was controlled by slab breakoff of the subducting Indian continental margin starting at about 25 Ma, they pointed out that this break-off model will be more efficient than the convective removal model in southern Tibet [57]. Kohn and Parkinson also apply a break-off in ~45 Ma to explain both the origin of the potassic rocks and the exhumation of the eclogite in High Himalayan metamorphic belt, they argue that slab breakoff readily explains the Eocene eclogites, Miocene partial melts, and late Eocene K-rich magmas in southeastern Tibet, and that metamorphic and plutonic ages help define the timing and rates of breakoff and extrusion [58]. Ding and his co-workers believe that break-off of the Tethyan oceanic crust and northward under thrust of Indian continent have played key roles in the ultra-K magmatism [41]. A more recent research by Guo and co-workers also supposed a geodynamic model for the petrogenesis of the rocks in northern Tibet with upwelling of asthenosphere induced by India’s underthrusting beneath Tibet [59].

VII. SR-ND-PB ISOTOPIC GEOCHEMISTRY OF THE ULTRA-K ROCKS IN LHASA BLOCK: EVIDENCE FOR INDIA SUBDUCTION UNDERNEATH TIBET?

Mo and his co-workers made a systematic research on the age, petrology, elements and isotopic geochemical of the postcollisional magmatic rocks across southern and northern Tibet, and focus on the igneous rocks in Lhasa block[42, 45, 60-61]. They classified three types of collisional and postcollisional igneous rocks in Lhasa block, following the identification of three main geochemical reservoirs in the lithosphere beneath the Tibetan plateau by the updated Sr-Nd-Pb isotopic dataset. Three diverse geochemical reservoirs could be identified by their Sr-Nd-Pb isotope features: (1) the North Tibetan Plateau Geochemical Province (NTPGP, $^{87}Sr/^{86}Sr$ = 0.7071

~ 0.7105, ε_{Nd} = -2 ~ –9, T_{DM} = 0.7-1.3 Ga, $^{206}Pb/^{204}Pb$=18.662~996, $^{207}Pb/^{204}Pb$=15.575~716, $^{208}Pb/^{204}Pb$=38.712~39.374), which has a stable, homogeneous reservoir since ~42 Ma, with a narrow range of isotopic ratios, as revealed by the widely spreading potassic rocks in Qiangtang, Hoh Xil, and West Kunlun belts; (2) the Neo-Tethyan mantle reservoir represented by the remnant oceanic crust preserved in the Yarlung Zangpo ophiolite ($^{87}Sr/^{86}Sr$ = 0.703000~ 0.706205, ε_{Nd} = +7.8 ~ +10, $^{206}Pb/^{204}Pb$=17.707~18.164, $^{207}Pb/^{204}Pb$=15.415~15.543, $^{208}Pb/^{204}Pb$=37.396~38.222); (3) Himalayan continental crust component represented by the basement and granitoids from Tethyan-, Higher and Lesser Himalayas, which having the highest Sr and lowest Nd isotopic ratios among the three reservoirs mentioned above, and relatively older Nd model ages (ε_{Nd} = -12~ -25, $^{87}Sr/^{86}Sr$ =0.733~0.760, T_{DM}=1.9~2.9Ga, the High Himalaya basement average $^{206}Pb/^{204}Pb$ = 19.500~736, $^{207}Pb/^{204}Pb$=15.833~843, $^{208}Pb/^{204}Pb$=40.212~241). Based on the proportion and interaction among the above-mentioned three reservoirs, three geochemical types of collisional and postcollisional magmatism can be recognized, each of which bears special implications for the deep processes and evolution of Lhasa block. The first type is Lhasa block inherent type showing similar Sr-Nd composition and strong affinity to NTPGP, namely, the Lhasa block should belong to NTPGP. The second is Tethyan oceanic crust affinity type of igneous rocks (including the I-type Gangdese granitoid batholiths, Linzizong volvanics, adakitic ore-bearing porphyries, etc.), which is origin-related to the subduction and recycling of the Tethyan oceanic crust, and relevant Cu-Mo-Au mineralization. The third one is the Himalayan type represented by the ultrapotassic volcanics in western Lhasa block, which exhibit a mixture trend between the two components of NTPGP and Himalayan continental crust. Therefore, the Sr-Nd-Pb data of ultrapotassic rocks will be an important evidence for the subduction of Indian continental slab beneath southern Tibet.

If the India continent subduction suggested by the above Sr-Nd-Pb feature of ultrapotassic rocks with ages ranging from 13 Ma to 28 Ma are true, then we could calculate the northward moving distance with a speed of ~50 mm/year of India by GPS data [62]. The results show that India frontiers should have reach and cross over the boundary between Lhasa block and Qiangtang to present. But we could not recognize any Sr-Nd-Pb clue in the postcollisional rocks in Qiangtang, since the isotopic feature of Qiangtang did not change since ~42 Ma. So the India plate have subducted beneath southern Tibet and reached Bangong Lake-Nujiang suture zone, but not subducted under Qiangtang. This India continental subduction model is perfectly consistent with the geophysical models [63-67] and He isotopic subdivision in Tibet [68].

VIII. SUMMARY

The widely spreading postcollisional potassic and ultrapotassic magmatic rocks in the Lhasa Block are tectonically linked to the N-S normal fault system. The ultrapotassic rocks are distributed in the areas to the west of 87°E, while the potassic rocks located from Shiquanhe to Lhasa, not limited by the 87 line. The age of ultra-K rocks range from 12 Ma to 28 Ma, slightly earlier than the shoshonitic rocks (9-24 Ma). The rock types are mainly trachyte, trachyandesite, basaltic trachyandesite, phonolite and tephriphonolite. They have extremely higher abundances of LREE and LILE, but are depleted in HFSE. They have old continental-like feature of high Sr and Pb and low Nd isotopic ratios, showing the affinity of the Himalaya basement, suggesting the subduction of the India plate beneath the Lhasa block which contributed to the source region of the rocks. The origin of the ultrapotassic rocks should be attributed to a break-off or delamination of the subducted oceanic/continental materials in Tibet.

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REPORT ON INTERNATIONAL CONFERENCE ON CONTINENTAL VOLCANISM (IAVCEI 2006)

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The International Conference on Continental Volcanism, sponsored by the International Association of Volcanology and Chmeistry of the Earth's Interior (IAVCEI), was held at White Swan Hotel, Guangzhou, China, May 14th to 18th, 2006. This meeting was financially supported by the Chinese Academy of Sciences, the Guangzhou Association for Science and Technology, National Natural Science Foundation of China, the Association for Science and Technology of the Guangdong Province and the Chinese Society for Mineralogy, Petrology and Geochemistry. It was organized by the Guangzhou Institute of Geochemistry and the Chinese Committee for IAVCEI. The conference comprises four-day indoor oral and poster presentation and two post-conference field excursions to the Emeishan large igneous province and the North China Craton, respectively.

The conference was successful by attracting over 200 scientists (including 53 students) from 28 countries/regions including Australia, Canada, China, Denmark, Finland, France, Germany, Iceland, India, Iran, Ireland, Israel, Italy, Japan, Mexico, Norway, Russia, South Africa, Thailand, Turkey, UK and USA. A number of them are world-class volcanologists, petrologists, geochemists and geophysicists on continental volcanism and chemistry of the earth' interior. This and the existing scientific program make the meeting stimulating at a very high academic level. As commented by Oded Navon, President of IAVCEI, the conference was a great success, the organisation was excellent, the scientific level was very high, the location was perfect and the field-trips were amazing. This view is shared by many participants.

The meeting opened with three plenary talks covering the thermal and mechanical structure of the continental lithosphere (Dan McKenzie, Cambridge), volcanism and climate change (Alan Robock, Rutgers USA) and volcanoes of China (Jiaqi Liu, Beijing). This was followed by four days of two parallel symposia on Chemistry, evolution and dynamics of the earth's interior and Continental volcanism: causes and consequences, respectively. The symposia were concentrated on nine thematic topics arranged into nine sessions which consist of 123 oral and 55 poster presentations. Each session opened with a keynote lecture followed by invited and contributed oral presentations and posters.

Participants to IAVCEI 2006 assembled in the White Swan Hotel, Guangzhou.

The symposium I started with the session on the Age, composition and evolution of the mantle. In a keynote address, William Griffin (GEMOC, Australia) described the nature of the shallow continental mantle and the marked differences between Archaean and post-Archaean shallow mantle. The North China Craton was the focus of several presentations using mantle xenoliths or alkaline-potassic intrusions as probes of the composition of the deep lithosphere in an attempt to constrain the change from cratonic to oceanic lithosphere during the Phanerozoic. Lithoprobes included the mineral chemistry of peridotite xenoliths, the elemental and isotopic geochemistry of peridotite xenoliths, the Sr-Nd-Hf isotope characteristics of syenites and the geochemistry of lamprophyres. It was clear that these record different aspects of the thermal and chemical evolution of the lithosphere (crust and mantle). Other presentations considered the multi-stage evolutionary history of mantle peridotites beneath the Izu-Bonin-Mariana arc and the Mediterranean, how kimberlites (Groups I & II) provide crucial information about lithospheric and sub-lithospheric processes, the complex origin of polymict xenoliths and the possibility that the Lherz lherzolite is a refertilised harzburgite. In-situ isotopic analysis reveals the complexity of the mantle system and the need for an understanding of the petrography of the rocks in question. The keynote address for the session “Mechanisms and effects of lithosphere destruction” was delivered by Dan McKenzie, Cambridge University, who reported the results of recent seismic investigations into continental lithospheric thickness. The most surprising result from this work is the finding that, contrary to previous belief, the Tibetan plateau is underlain by very thick lithosphere (to depths of 300 km), with the implication that models for "delamination" in this region are not correct. Contributed and invited presentations addressed lithosphere destruction in different regions of the world (e.g., North Atlantic, Arabia) but the overwhelming majority of the talks and discussion focused on how the deep, ancient and refractory lithosphere in the eastern block of the North China craton was removed during the Mesozoic. Models ranged from no destruction (i.e., stretching followed by new lithosphere accretion due to upwelling) to transformation (through melt-rock reaction), through removal via thermal erosion or density foundering (delamination). The consensus that emerged is that more data (particularly geophysical data) and plausible physical models are required. The discussion on the lithospheric evolution continued in the session "Ultradeep samples and the Earth's interior". The keynote talk by Craig O'Neil used new modelling approaches to evaluate the conditions required for the survival of continents in a convecting Earth. The presentations that followed used seismic tomography, gravity and dynamic topography to argue for whole-mantle flow and to show that the African and Pacific superswells are different from the surrounding mantle. Seismic tomographic models were used to suggest that cratonic roots may extend deeper than commonly supposed. Remnant blobs of subcontinental lithosphere in the ocean basins may affect the isotopic systematics of oceanic basalts and may explain the Re-Os data indicative of ancient depleted mantle beneath the ocean basins. Fluid inclusions in diamonds were used to define the nature and evolution of silicate to carbonate fluids in the deepest lithospheric mantle. The fate of subducted material was the focus of several presentations covering the nature and origin of eclogites (recycled or underplated magmas), the contribution of subducted material to the deep mantle and basalt source regions and post-spinel transformations of subducting material in the deep Earth. Fe isotope fractionation in mantle minerals were shown to have some utility in understanding subduction and partial melting processes while Tl isotopes may turn out to be a unique tracer for subducted material in basalt sources.

Considering the current plume debate, a session is arranged on the role of mantle plumes and plate tectonics in the generation of Large Igneous Provinces. Ian Campbell's keynote used the extent of pre-volcanic uplift and the occurrence of picrites in large igneous provinces (LIPs) to validate the plume hypothesis. In the presentations that followed all of the speakers advocated a direct relationship between mantle plumes and LIPs. Alternative hypotheses were conspicuously absent. Presentations covered a broad range of topics from the classification of LIPs, placing special emphasis on Archaean and Proterozoic LIPs, including dyke swarms and layered intrusions to mantle differentiation achieved through gravity separation of magnesium and calcium silicate perovskite in the ultra-low velocity zone above the core, leaving lighter SiO_2-rich mantle that is preferentially entrained in plumes. Presentations on the Siberian Traps were of special interest in the light of a recent suggestion that this LIP lacks uplift prior to volcanism and therefore cannot be due to a mantle plume. Melt inclusion studies in olivines from the Siberian Traps revealed that they formed at a pressure of 7 to 9 GPa from high temperature mantle (i.e., excess temperature of 400 ^{o}C) - melting conditions that can only be achieved in a mantle plume. The LIP that attracted most interest was the well-preserved late Permian Emeishan flood basalt province in south-western China. Five talks were presented on this LIP covering domal uplift prior to volcanism, geochemistry and geochronology. The age the LIP (initiation and termination) was hotly debated.

The symposium II started with the session “Sources and Origin of Continental Volcanism”. In a keynote talk, Helen Williams emphasized the distinction between the chemical and isotopic compositions of many continental "basalts" and typical MORB and/or OIB and argued that SCLM remains a viable source for many continental mafic rocks particularly continental potassic basalts. In the presentations that followed descriptions were given of the petrology and geochemistry of Phanerozoic igneous rocks from Turkey, northern Patagonia, northeast Iran, and western North America, and continental igneous rocks from China. A common theme in many of these talks was the issue of the relative roles of sublithospheric mantle, subcontinental lithospheric mantle (SCLM) and continental crust as sources for continental magmas. Other speakers suggested that even OIB-like sodic continental basalts could also be derived from SCLM if the mantle were previously metasomatized by carbonate rich fluids. Clearly an important remaining question is what compositions of SCLM can actually undergo partial melting and if refertilization of SCLM with basaltic components and volatiles is necessary before such melting can occur. Trigger mechanisms for continental magmatism were also widely discussed in this session, including lithospheric "delamination". The latter has become one of the most popular mechanisms of producing post-orogenic continental magmatism, but additional studies will be needed to critically assess what portions of the mantle or continental crust can actually be induced to melt during such a process. The keynote presentation by Ken Sims (WHOI) provided an accessible overview of how U-series disequilibrium can be used to provide constraints on the time scales of magmatic processes. Presentations in this session covered a range of inter-related topics : experimental data on nucleation of CO2 bubbles in alkali melts as a potential mechanism to trigger wallrock fracturing and the formation of xenoliths; how temporal changes in crustal assimilation constrained the magmatic plumbing systems during the development of the East Greenland LIP, and emplacement timing using pressure estimates from fluid inclusions in the Skaergaard intrusion with a cooling model for the intrusion. Several presentations used elemental diffusion profiles (Li, Be, B, Sr, Ba) to determine residence times for phenocrysts in magma chambers. The causes and implications of dome-forming to lava-forming eruptions within subduction zones were considered in terms of crustal heat flux and differentiation mechanisms. Adakitic magmas in China were investigated in several presentations using field data, experimental constraints and Cu-Au mineralisation.

The keynote lecture by Else Raghnild-Neumann (Oslo) in the session "Silicic & Alkaline Magmatism**'** covered the detail of the Permo-Carboniferous Oslo Rift/Graben. This was followed by presentations on the Tertiary Sierra Madre Occidental and Gulf Alkaline provinces of Mexico, the Snake River Plain-Yellowstone bimodal volcanic field of northwestern USA, and large volume rhyolitic eruptions from the Afro-Arabian flood basalt province. Age and petrogenetic aspects of episodes of bimodal and A-type magmatism across the North and South China cratons were discussed, and thermomechanical effects on crustal structure and rheology during 'ignimbrite flare-ups' were also presented. Two important issues arising from this session were that mass balance calculations and the changing thermal profile of the crust with time are important considerations in understanding the generation of widespread and large volume (>0.1 Mkm^3) silicic magmatism. Large thermal and material inputs to the continental crust are clearly required, but that the relative proportion of crustal partial melting, especially of Precambrian crustal sources, to mantle-derived magmas often appears to be small. Results of thermomechanical modelling indicate that the crustal profile becomes hotter and more ductile with time in response to the thermal and mass input of mantle-derived magmas. This can lead to the development of larger silicic magma chambers, catastrophic eruption pulses and the eruption of batholiths.

The consequence of the continental volcanism was grouped into the environmental and economic aspects. Papers in the session "Environmental impact of continental volcanism" covered the entire range of the scale of volcanic eruptions, from the effects of small Indonesian eruptions on sulfur depositions in peat and subsequent effects on Asian haze, to the effects of flood basalts on mass extinctions. In his keynote, Hans Graf showed how permanently degassing volcanic systems to super eruptions have different effects on the troposphere-stratosphere system. Several papers discussed climate model simulations of the effects of large explosive volcanic eruptions, showing how low latitude eruptions produce a winter warming response, while high latitude eruptions reduce the Indian and African summer monsoons, producing warmer temperatures and reduced precipitation. Open questions remain as to whether much larger eruptions can cause ice ages or mass extinctions. Simulations of the climatic effect of the Toba eruption showed large cooling lasting a decade but no ice age initiation. The Deccan and Siberian Traps, however, could have emitted enough material to cause significant climate change over a significant period, but we are still lacking good estimates of the rate of emission and length of large emission periods. As aerosols have a short lifetime in the atmosphere, continuous emissions over a large period of time, lasting decades, would be necessary for change large enough to cause mass extinctions. Papers also addressed observations of volcanic eruptions, including ice core records of past volcanism and remote sensing of sulfate emissions from African volcanoes.

Peter Lightfoot gave a keynote talk on the Noril'sk-Talnakh Ni-Cu-PGE deposits, arguably the richest of all mineral deposits and source of much of our understanding of the formation of magmatic ores. The presentations that followed involved the Pechenga deposits in Finland; the Pd reefs in the Skaergaard intrusion; deposits in the Emeishan LIP in China; the Platreef PGE deposit of the Bushveld intrusion and ore formation and mantle dynamics. Attempts were made to establish a geochemical criteria capable of distinguished ore-bearing and barren continental volcanic provinces. The final session dealt with deposits in China including the recent work on the Jinchuan deposit and economic deposits associated with the Emeishan province especially PGE deposits related to the low-Ti mafic-ultramafic intrusions and Fe-Ti oxide deposits in Fe-rich alkaline intrusions.

The two post-conference field trips were both informative and fruitful. The four-day trip to North China, led by Drs. Hongfu Zhang and Jian-ping Zheng, offered participants the opportunity to visit the key features of the magmatic/metamorphic rocks emplaced at different time in Shandong Province (eastern North China Craton). The investigation into the Taishan Archean igneous complex, Mengying Paleozoic kimberlites and xenoliths/xenocrysts, Yinan and Jinan Mesozoic magmatism and Shanwan Cenozoic basalts & xenoliths in highlight the temporal change of this re-activated craton. During the nine-day field excursion to the Emeishan large igneous province, which was led by Drs. Yigang Xu, Bin He and Hong Zhong, the spatial variations in thickness of the Maokou Formation, the contact between the Emeishan basalts and overlying and underlain sedimentary sequences and syn-doming sedimentation have been investigated. These data have been taken as evidence for a rapid, km-scale crustal doming prior to the Emeishan volcanism, which is relevant to the currently debate on mantle plumes. Other stops have been made to visit the volcanic succession across the domal structure and the layered intrusion and associated V-Ti-PGE mineralization.

The objective of IAVCEI 2006 was to bring together geologists, petrologists, geochemists and geophysicists with diverse approaches and methodologies to discuss and to change ideas on a wide range of topics related to continental magmatism. This has obviously been achieved during the indoor symposia and field trips, with participants enthusiastically involved in the stimulating discussion. Some contributions to *IAVCEI 2006* will be selected for publication in two special volumes in Lithos and Episodes.

Left: Participants to North China trip were standing on the Taishan Archean complex.

Right: A volcanological class on the river bed near Daqiao, Emeishan LIP.