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# PROGRESSES ON HOLOCENE VOCANOLOGY RESEARCH AFTER 2007

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ABSTRACT: In this paper, we briefly reviewed the main progresses on Holocene volcanology research. The review includes the following eight topics: 1. Recently discovered Holocene vocanoes: Ma'an Shan, Dalaibinhutong, 371 and 358 High Land volcanoes in Bila River basin, Inner mongolia, Yan Shan, Gao Shan, No.10 basin, Xiao Donggou and Zigong Shan volcanoes in Chai He-A'er Shan Volcanic cluster, Gezi Shan volcano in Xilinhaote volcanic cluster, Liandanlu volcano in Wulanhada volcanic cluster; 2. Detail eruption sequence and frequency: Cenozoic volcanic clusters in China mostly are products of multi-eruptions, and even one single volcano is usually composed of multi-eruption sequences; 3. High resolution reconstruction of volcanic edifices: detail studies on petrology, petrography, phase sequence and large scale 3-D mapping of individual volcano will help to reconstruct the volcanic edifice in detail; 4. Origin, morphology and distribution of volcanic clasts: high-tech analysis methods have and fractal theory from mathematic science have been used to study the volcanic clasts' origin; 5. Studies of pyroclastic flow, base surge and lahar deposits; 6. Subdivision of volcanic fall deposits; 7. Volcanic eruptions and related structures; 8. Resources from volcanic relict and volcanic disaster.

KEYWORDS: Holocene volcanoes, Volcanology, Eruption sequences, Volcanic clasts; Main progresses

Volcanic activities are one of the most important geological processes and they are closely related to the formation of the all layers of the planet Earth. Volcanology focuses on the research on all processes associated with volcanic eruptions which includes the magma transportation through the volcanic pipe, the eruption itself and the deposition sequences and environments of the volcanic claasts. Volcanology is the basic for the study of volcanic resources, eruption related climate change and volcanic hazards, and it is also vital for us to understand the crustal and mantle compositions, deep processes within magma chambers and associated regional tectonic events. With the development of the new technology of volcanic products analysis, we have made lots of progresses on the study of Holocene volcanoes.

## I. RECENTLY DISCOVERED HOLOCENE VOLCANOES.

China's holocene volcanoes are predominantly located in the eastern China and around the Tibet plateau. Research on China's holocene volcanoes started from 1990's (Yang et al., 2009). Volcanoes discovered by these previous studies include: Changbai Mtn Crater lake; Jinlongdingzi volcano in Longgang volcanic cluster; Jingpo crater lake, Wudalianchi, Laohei Shan, Huoshao Shan, Keluo, Er'ke Shan, Xiaogulihe in Heilongjiang province; Ma'an Shan-Leihu Shan in North Hainan province; Weizhou island (Li et al., 2005); Tengchong volcanic cluster in Yunnan province; Tulufan, Xitianshan, A'shi, Kekexili in Xinjiang province etc. Hong et al., 2005 published preliminary research on the volcanic hazards evaluations. Recently, some holocene volcanoes in Quaternary volcanic clusters were discovered in Bila River watershed, Chai He-A'er Shan, Xilinhaote and Wulanhada of Inner Mongolia.

In Qiangtang area of Northern Tibet, some holocene mud volcanoes were discovered too (Xie et al., 2009). Discovery of the holocene volcanoes in eastern Inner Mongolia is one of the most important progresses on volcanology research in China, which sheds light on the understanding of the crustal structures, Neotectonic activities, volcanic hazards prediction and the economic development of the local areas.

*1. Wulanhada Holocene Volcanoes*

Wulanhada Quaternary volcanic cluster is located in Wulahada area of Inner Mongolia with coordination of E 113°01′～113°32′and N 41°26′～41°38′, and about 300 km away from Beijing. It is between the Bainaimiao-Wendu'ermiao paleo microplate of northern margin of the North China craton and Neoproterozoic accretionary wedge and it belongs to southern end of the Cenozoic Datong-Daxing'anling volcanic belt. This volcanic cluster covers an area of about 280 km2, and includes about 30 volcanoes. The distribution of the volcanoes is controlled by the NE-NW basement faults and all the eruptions are fissure eruptions or fissure-center eruptions. Main eruptions occurred in two periods of late Pleistocene (21.05±1.79 ka BP) and Holocene (Bai et al., 2008). In late Pleistocene, eruptions are mostly fissure eruptions forming a series of along faults distributed gentle splashed lava cones, lava dam and hypabyssal dikes. There are three Holocene volcanoes distributed along a line of NE direction. They are composed mainly of tephritic cinder cones and lava flows. Cinder cones and the crater are well preserved. Lava flows are well exposed and cover an area of about 180 km2, which is the main component of this volcanic cluster. The three so called " alchemy furnace" volcanoes have deep and round craters imitating the mouth of a furnace. The profile, structure and eruptive styles are similar for all these three volcanoes, but the ages and eruption scale are different. All three volcanoes started with explosive eruptions followed by lava flows. Lava flows are mainly pahoehoe with some aa flows. Pahoehoe lava flows are black or dark grey in colors with lengths of about 10-18 km and widths of 1-3 km and thickness of 5-15 m. The front of the lava flows are usually fan shape with a thickness of only 1-2 m. Lava branch flows are well developed at the front and along the margin of the main flows. Pahoehoe lava flows have complicated surface patterns with large ratio of surface area/ thickness indicating low viscosity of the magma. Aa flows are relatively smaller scale and late and distributed close to the crater or the cinder cone. Due to local topography, lava flows mostly flow toward SE to fill the gullies and basins. To the east and south of these three volcanoes, seven lava dammed lakes were constructed. Based on the sequences of all the lava flows, the north and south "alchemy furnace" volcanoes are older and the middle one is younger. All three volcanoes are strombolian volcanoes. Let us take the middle one as an example. This volcano is located about 7.5 km to the SW of Wulanhada. The coordinates of the crater is N41°36′and E

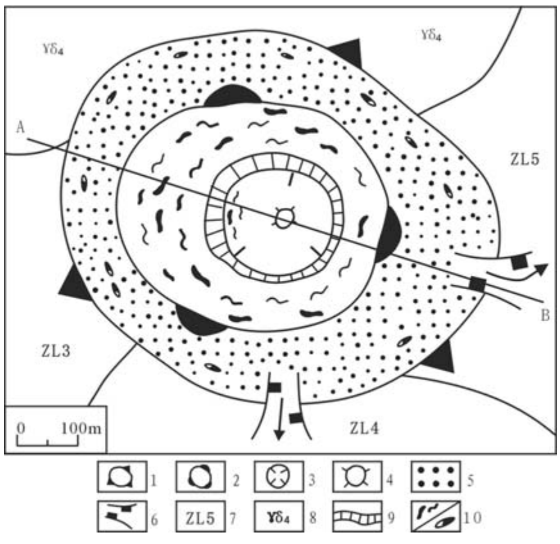


Fig.1 Geological map of cone, Middle Cupola

1-fallen cinder cone; 2-spatter cones; 3-crater; 4-crater cone; 5-cinder; 6-magma overflow exit; 7- Lava flow of the Middle Cupola; 8-Variscan granodiorite; 9-crater edge; 10-lava pie/ volcanic bomb

113°07′. It is composed of tephritic cinder cone and lava flows. The cinder cone lies above the Variscan granodiorite. It has a round surface profile, and is about 85 m tall with an diameter of 780-620 m and is composed by an earlier scoria cone and later splashed magma dome on top(fig.1,2). The earlier scoria cone has gentle slope. The bottom of the scoria cone is constructed by black pumice with diameters of about 4-6 cm, while the top of the scoria cone is full of black pumice with diameter below 3 cm. The above splashed magma dome is composed of dark brown, purplish ignimbrite. The crater is about 26 m deep and the west rim is higher than the east rim with an average width of about 3-10 m. The diameter of the volcanic neck is about 70 m, and a later lava dome is on top of the neck with a diameter of about 20-30 m(fig.2). Lava flows flew out from the south and the east of the crater rim and mostly flew toward SE and the front of the lava flows covered the Holocene alluvial deposits and mash deposits with an area of about 100 km2. Lava flows can be divided into five flow units. The first four units flew toward the basins to the SE of the volcano. The fronts of these units arrived at Baiyin Dao and formed three dammed lakes on their way. These lava flows have length of about 19 km, width of about 1-3 km with the narrowest part of 300 m, and thickness of 3-10 m. Lava domes and gas exclusion cones were developed along the fronts. The domes are usually 3-10 m tall with diameters of about 10-30 m with some exceptions of about 50 m. On the top surface of the domes, radiating pattern fractures were developed. The fifth unit flew toward E and W. It is smaller scale and relatively later AA flows. At the beginning, the eruptions of were quite explosive. Highly fragmented magma were shot to the sky and then fell off on the ground due to gravity to form large scale tephra cone. After the magma pipe was opened due to the first eruption and the decrease of the content of volatiles, and the decompression effect the eruptions became less and less explosive. Highly ductile hot magma fragments splashed out of the vent and fell on the rim of the crater welding to each other to form smaller scale but very steep splashed cone on top of the tephra cone. Then due to the dramatic decrease of volatiles content, and the increasing magma exffusive rate, eruptions became effusive instead of explosive. Lava flows effused from the neutral buoyancy surface along the bottom of the cone. Lava flows became shorter and shorter as time goes by and the effusion of the AA flow indicated that the volcanic activities of the middle cupola volcano was getting close to the end. The appearance of the lava dome at the vent indicated the end of all volcanic activities for this volcano.

The volcanic activities of Wulanhada has a pattern of moving from NE to SW. Cinder cones, craters and lava flows are all well preserved. The lava flows cover the Holocene alluvial deposits, so the age of these volcanoes must be younger and in Holocene range.

*2. Gezi Shan Volcano in Xilinhot*

Gezi Shan volcano in Xilinhot-A'baga volcanic cluster is located to the SE of the city of Xilinhot. The coordinates of the volcano is 116º 15′25″E and 43º 26′ 30″N. Quaternary Xilinhot-A'baga volcanic cluster covers an area of about 9300 km$^2$ and it has about 284 volcanoes. Late Pleistocene is peak of all volcanic activities in the volcanic cluster. Gezi Shan volcano is an representative of Holocene volcanoes here. It is composed of cinder cone, pyroclastic sheet and lava flows. The

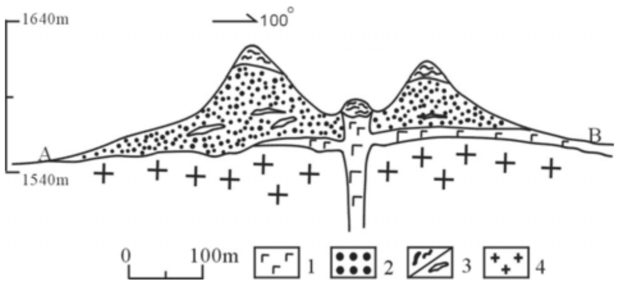

Fig.2 Profile of the Middle Cupola

1-basalt; 2-cinder; 3-lava pie/ volcanic bomb; 4-Variscan granodiorite vent experienced multi-collapse. This volcano has a surface shape of ellipsis with the long axis of 1.5 km long and the short axis of 1.2 km long. The height of the volcano is about 110 m and the angle of repose is about 25-30º. The areal fall deposit is composed of black and dark grey scoria with diameters of about 1-2 cm, and some volcanic bombs. Spatter cone of welded agglomerate with diameter of about 800 m piled on top of the lose packed cinder cone. The west and northeast of the cinder cone developed lava effusion exits. The west exit collapsed and left an depression 30 m deep with diameter of about 80 m. Part of the cinder cone was pulled apart from the cone and transported about 1 km away from the volcano by the lava flows effusing from the northeast exit. Due to the fast drainage of the magma chamber, the roof of the chamber collapsed several times to form a caldera with a diameter of about 450 m. There are later lava domes developed in the caldera and diabase dikes along intruded along the ring fractures. Early eruptions also formed large fallout sheet mostly to the southeast of the Gezi Shan. It is mainly composed of black or dark grey scoria and ash with diameters of about 3-7 mm. The largest can be about 10 mm in diameter. The thickness of the fallout sheet decreases away from the volcano. The primal thickness is about 2-3 m and it decreases to about 20-25 cm thick about 6 km away from the crater. The existence of the fallout sheet indicates the explosive nature of the early eruptions, and the distribution pattern was controlled predominantly by the nature of the season wind. After the early explosive eruptions magma effused from the west and northeast of the cinder cone to fill the depressions and basins to the two sides of the volcano. Different flow units overlap each other and form large scale lava plateau covering an area of about 48 km2. Lava flows effused from the west exit flew toward west firstly and then toward south. Lava flows from the north exit flew around Gezi Shan toward north and then flew toward south too and flew over the lava flows from the west exit. Most lava flows are pahoehoe, while there are very few aa lava. Pahoehoe lava flows are relatively larger scale and have lengths of about 12-16 km, width of about 2-3 km and thickness of about 10-15 m. The fronts of these flows are fan shape with thickness of about 1-1.5 m. When thin lava flows flew on the top of wetlands with extremely low speed there usually developed many fumaroles. Fumaroles within Gezi Shan lava flows distributed mainly at A'dunchulu and the fronts of these flows and almost all of them were well preserved with very little weathering and erosion (fig.3). The heights of the fumaroles are usually 40-90 cm, diameters 3-4 m (smallest, 1 m, biggest, 7-8 m). Lavas imbricated along the rim of the fumaroles. The thickness of a single layer of lava is about 1-2 cm. Aa flows are very few and distributed only close to the cinder cone and is the late products of the volcanic eruptions. Volcanic activity history of Gezi Shan includes early explosive eruptions, spatter cone formtion, and later effusive eruptions. All volcanic structures were well preserved. The pahoehoe lava flows lie over Quaternary alluvial deposits, which indicates that the eruptions happened in Holocene.


Fig 3 Gezi Shan fumarolic cone

*3. A'er Shan-Chai He Holocene Volcanoes*

A'er Shan-Chai He Quaternary volcanic cluster is located in the middle part of Da Xing'anling Mtn (Bai et al., 2005, Zhao et al., 2008) with an area of about 1000 km2 and have about 30 volcanoes. Yan Shan, Gao Shan, No.10 Basin, Xiaodonggou, and Zigong Shan volcanoes are Holocene volcanoes.

The distribution of all these volcanoes is controlled by the NE striking basement faults. Most of them are composed of cinder cones and lava flows, while Yan Shan and Gao Shan have fallout sheets developed. Lava flows are mostly pahoehoe and there are some aa flows and blocky lava flows. Well preserved fumaroles and lava domes were found in the pahoehoe lava flows. Rocks are mainly alkalic basalt and most volcanoes are strombolian, while some are sub-plinian. All volcanic structures are well preserved without much weathering and erosion. Distribution of lava flows is controlled by local topography and they blocked Halaha river to form a series of dammed lakes and they lie over Holocene alluvial deposits. Two pieces of carbonated wood were collected about 400 m to the SW of Yan Shan. $^{14}$C ages are 1990±100 和 1900±70a.B.P respectively (Bai et al., 2005). Hot springs are well developed in this volcanic cluster, and there are also unfreezing rivers in this area. The hot springs distributed along the NE striking basement faults, which tells us that this volcanic cluster can be broadly defined as active volcanic cluster. Based on the sequences of lava flows, volcanic activities moved from NE toward SW.

*4. Bila River Holocene Volcanoes*

Bila River volcanoes of Nuomin River volcanic cluster are located at the east slope of the north section of the Da Xing'anling Mtn and belong to north session of the Cenozoic Datong-Da Xing'anling volcanic belt. Most volcanic activities happened in late Pleistocene（25.19 ±2.14kaB. P）and Holocene. Volcanoes distributed along the middle and upstream of Nuomin River, Bila River and Kuile River. The volcanic cluster covers an area of about 850 km$^2$ and there are about 27 individual basanite volcanoes formed by magmas coming from the partial melting of upper mantle. There hawaiian, strombolian, sub-plinian, maar , and mixed volcanoes in this volcanic cluster. Volcanic activities moved from NE to SW. Eruptions in Kuile River occurred the first, so the rocks were weathered the most. Eruptions in Bila River area are late in time, so the rocks are relatively fresh. Holocene volcanoes mostly distributed in Bila River area, which include Dalaibinhutong, Ma'an Shan, 371 and 358 highland. All volcanic structures were well preserved without much weathering and erosion. Lava flows are black and dark grey in color and show different shapes, which is called by local people as "stone ocean" where there is no plant growing on top. These lava flows flew along the Bila River and blocked some of its branches to form several dammed lakes. To the south of Dalaibinuo dammed lake, the lava flow lies over Holocene alluvial deposits which indicates that the lava flow is Holocene age. Lava flows of Ma'an Shan volcano is similar as those of Laohei Shan in Wudalianchi which erupted at 1721-1725. The stratigraphy relationship between these lava flows and Holocene alluvial deposits tells us that they formed in Holocene. 371 highland in Bila River valley is the representative of the Holocene haawaiian volcano. It is a shield volcano with a slope angle of only 2-3°. The vent is located on the top of 371 highland and it is a shallow depression. Lava flows here are mainly pahoehoe lavas and they flew toward SE and NW. The lava flows heading north blocked the Zhawen River and made it flow toward Bila River. The lava flows heading south is about 8 km long and changed the flow of Bila River to form dammed lakes. Ma'an Shan volcano is sub-plinian with coordinates of E123º9′50″，N49 º33′30. It is composed of cinder cone, fallout sheet and lava flows. There are two vents constructing a duplicated crater. The two vents are aligned along EW direction and share part of the rim in between. This shape looks like a saddle, so the volcano was given a Chinese name of "Ma'an" which means saddle. The height of this volcano is about 264m and the long axis and short axis of the bottom of it are 1.5 km and 1 km respectively. Both vents are horseshoe shape and the west one is 58 m deep with diameter of about 500 m. The cinder cone is mostly composed of the scoria from explosive eruptions and the cone has slope angle of 18-20°. On the top of the cinder cone there is an spatter cone of ignimbrite with very steep slopes of 25-30°or even 60°. About 2.5 km away from the cinder cone, the thickness of the fallout sheet is about 1.5 m. This tells us that eruption column formed above the vent during the eruption. Scoria covered Holocene colluvium. Grain size is quite homogeneous of about 1-3 cm with rhythmic layering. Pahoehoe lavas from the east vent is earlier than the west vent. Lavas flew above the fallout sheet and lavas from the west vent flew toward Bila River valley to form locally called "stone pond" (fig.4). Lava blocks have diameters of about 1-2 m. Along the ridge of the lava flows collapsed depressions were formed and some of them can 2 m deep. After early explosive eruptions, volcanic activity paused for Ma'an Shan volcano, and then the vent was even clogged. Then spatter cone was formed from two vents. After this, effusive eruptions took over. The effusion of AA flow close to the vent is the sign of the end of the volcanic activities. Dalaihubintong volcano is a stratovolcano. Main vent has coordinates of E123º10′45″ and N49 º28′50″. This volcano is one of the largest Holocene basaltic volcano in Da Xing'anling area. First layer of the stratovolcano is a shield lava layer. Above this layer there is spatter layer and a bunch of parasitic vents. The long axis of the shield layer strikes NNE with a length of about 3 km and width of about 2 km and covers an area of about 6 km2. The north slope is gentle with an angle of about 8-10° while the south slope is steep with slope angle of 15-20°. The bottom of the shield layer is pahoehoe and the top is aa flow. The western side of the shield blocked the branch of Bila River to form a 4 $km^2$ dammed lake. On the top of the shield layer, one spatter cone and one lava dome are aligned along EW direction. The eastern spatter cone is about 110 m high, and the bottom surface has a diameter of about 1000 m. The diameters of the crater and vent are 500 m and 100 m respectively. Lava dome is to the west of the spatter cone. It is about 600 m in diameter and about 116 m in height. To the north of the shield layer there are 6 parasitic vents distributed along a line. They have diameters of about 100-150 m, the largest 300 m, and depth of about 10-20 m with the deepest of 50 m. Some of this vents are full of plants now, which is locally called underground forest. Dalaibinhutong volcano started with effusive eruptions to form the shield layer first, then as the effusive rate kept decreasing, eruptions are less concentrated to the vent of the spatter cone.

Fig 4 Ma´an Shan blocks lava

## II. HIGH RESOLUTION ERUPTION SEQUENCES AND FREQUENCY

Study of eruption history and frequency is the base of volcanic eruption prediction and hazards evaluation. Previous research tells us the Cenozoic volcanic clusters in China are all products of multi-stage eruptions ( Fan, 2008; Bai et al., 2006; Chen et al., 2007; Hu et al., 2009; Liu et al., 2008; Yang et al., 2007; Peng et al., 2008). A'baga-Xilinhot volcanic cluster is a representative of the ones that have been active from Miocene to Holocene. Some volcanic clusters have been active from Pleistocene to Holocene, such as Longgang, Qiongbei, and Wulanhada volcanic clusters. Even one single volcano experienced multi-stage eruptions (Bai et al., 2008). We did high-resolution and large scale mapping of volcanoes using volcanology physics, chemistry, and remote-sensing methods. First of all is to reconstruct the eruption sequences of the volcano. Then, compare the individual volcanoes to work out the eruption history and sequences of the whole volcanic cluster. Combined geochronology, morphology(Luan et al., 2009), the degree of weathering (Zhang et al., 2009) provided vital evidence of the ages of these eruptions. For example, Chabai Mtn volcano has a long eruption history ( Yang et al., 2007; Liu et al., 2008; Fan et al., 2007; Li et al., 2007). This history can be divided into three stages. The early stage started from Pliocene. Rocks are trachybasalt to trachyte (2.14 Ma). Middle stage is from early Pleistocene (0.81Ma and 0.92 Ma) to middle Pleistocene. Rocks evolved from basaltic to trachyte and trachyandesite. Late stage is from late Pleistocene to Holocene. Rocks evolved from basalt to alkaline rhyolite. Trough detail research we have reconstructed high resolution eruption sequences for Changbai Mtn volcano for the recent 5000 yrs. Indicated by drilling core study, except for the famous "Qian Nian huge eruption", there were earlier eruptions existed. In between, mud layers were observed which means there was a quiet period of time after the earlier eruptions. People collected two pieces of carbonated wood from this mud layer which gave us ages of 2040BP and 1065BP (Liu et al., 2008). Based on these ages, there were large scale alkalinerhyolitic volcanic activities before the famous "Qian Nian huge eruption". Except for this, written historic record also gives us recording as that there were small scale eruptions in 1668BP, 1072BP and 1903BP(Wu et al., 2009). The corresponding eruption deposits are all found in the field for all these small eruptions. For example, on the south slope of the crater lake and the north slope there are black trachytic ignimbrite overlying grey alkalicrhyolitic pumice of the famous "Qian Nian huge eruption", which can be regarded as the evidence of the later eruptions(Fan, 2008). Yang et al., 2006 found a layer of dark grey pyroclastic flows overlying the deposits of the 1668 BP fallout tephra, and they concluded that this is the product of the 1903 eruption. All above tells us the frequency of the Changbai Mtn is about 1000 years. The better and higher resolution we can get for the volcanic eruption history, the better and more reliable the prediction of future eruptions will be.

## III. HIGH RESOLUTION VOLCANIC EDIFICE AND MULTI-DIMENSION STRUCTURE

Volcanic activities are discontinuous temporally and spatially. The distribution of eruptive materials is limited spatially and some features are quite local, unstable and heterogeneous. We need to take the crater as the reference, and start with petrology, lithofacies and facies sequence study, then combine these with large scale 3-D mapping of the volcanic edifice. After the mapping, we need to systematically study the volcanic products including their morphology, origin and their mechanical parameter during formation and transportation. The reconstruction of high-resolution volcanic edifice will provide vital evidence for the study of eruption nature, eruption sequences, volcanic geochronology and physical eruption history, prediction of future eruptions and hazards evaluations. Recent high resolution mapping include the following volcanoes: Changbai Mtn Tian Chi (Wei, 2010); Jinlongdingzi, Longgang volcanic cluster (Bai et al., 2006); Bila River, Ma'an Shan; Chai He-A'er Shan Yan Shan (Zhao et al., 2010); Gezi Shan, xinlinhot; Cupola volcano, Wulanhada ( Bai et al., 2008). Based on the detailed volcanic edifice map, we accurately determined the distribution of volcanic products, estimated the volume of the eruptive materials and energy released and the heights of some of these eruption columns and work out the main factors influencing the length of lava flows (Wei et al., 2005). Combined all above with geochronology analysis, the 3-D volcanic edifices were successfully reconstructed and the eruptive sequences were determined.

## IV. GRAIN SIZE DISTRIBUTION, MORPHOLOGY AND ORIGIN OF PYROCLASTIC MATERIALS

Study of pyroclastic materials are changing from qualitative to quantitative. Morphological features of different origin pyroclastic materials were determined by using new technology analyses on grain morphology, grain size distribution, composition and parasitic minerals and the using of mathematical fractal theory. The purpose of this work is to determine the physical and mathematical parameters of the different types of volcanic products and then study the processes by which different eruptive mechanisms switch to each other. Intensely studied Holocene volcanoes include Changbai Mtn Tian Chi (Yang et al., 2007), Long Gang, Jilin province (Liu et al., 2009; Bai et al., 2006) and A'er Shan, Inner Mongolia. Pyroclastic materials from Changbai Mtn Tian Chi have been studied since 1990's. They have been divided into three categories: fallout tephra, pyroclastic flow and nuee ardente. Prebious workers concluded that the transportation of the pyroclastic materials is predominantly by laminar flow based on the vertical variance of the grain size from the cross section. Yang et al., 2007 concluded that the pyroclastic materials from the famous "Qian Nian huge eruption" is poorly sorted while the nuee ardente materials are well sorted. Lithic fragments and pumice become smaller in size when it is getting farther away from the crater, which indicates that there are differentiation during transportation due to gravity and mechanical erosion. Pyroclastic materials can be hydrated during transportation. But as it is getting far away from the crater it is harder to be hydrated, which indicates that during transportation the materials experience degassing processes which increase the viscosity and strength of them to force them to deposit. Rate of hydration plays an important role in transportation distance of the pyroclastic materials. Liu et al., 2009 did some further research on the Si Hai pyroclastic flow in Long Gang volcanic cluster, and they reassured that Jinlongdingzi volcano is sub-plinian volcano. Grain size distribution curve shows that the materials experienced gravitational differentiation during transportation and settlement. Recently, as the technology allowed, people started to do grain size distribution study for grains <0.005mm. Grain size fractal number (D) is an index to be used to distinguish different eruptions. Phreatic eruptions have the highest D value, and then is phreamagmatic eruptions and magmatic eruptions. Morphology of pyroclastic materials under microscope is another important criteria to distinguish different eruptions. Clasts from phreatic eruptions are mostly lithic blocks from the wall rocks. These clasts have good roundness and smooth surfaces, and are predominantly sand size or silt size. No vesicles developed. Quartz clasts developed ductile scratches on their surfaces. Phreamagmatic clasts are usually sub-roundness, and the grain size changed a lot. Most grains are volcanic sand or volcanic lapilli. The clasts have vesicles with crack on the vesicular surfaces, and the vesicles are usually filled with secondary minerals. Magmatic eruption clasts are often very angular. Vesicles are usually pipe shape, egg shape or round shape. Some of the clasts have smooth but not flat surfaces. Zhang et al., 2009 used SEM and XRF to study the plagioclase fragments' surface features and they concluded that the younger the eruption, the lower the degree of order, and the higher the temperature it recorded. Morphology of the plagioclase phenocrysts might be related to the eruption age and eruption temperature.

## V. PYROCLASTIC FLOW, BASE SURGE AND LAHAR

Pyroclastic flow, base surge and lahar are all important content of volcanology. Recently, the focus of this research has changed to the study of deposition phase sequence and phase model. Petrography, phase sequence are the basics to form volcanic stratigraphy and reconstruct volcanic structure and eruption history.

*1. Pyroclastic Flow*

Pyroclastic flow is hot high density flow rich in clasts and gas. There are mainly two types: subaerial and submarine. Subaerial pyroclastic flow is composed of block and ash flow, lithic fragment flow and pumice flow. Recent research all focus on pumice flow. Sheet like pumice flow deposits has flow units, eruption units and cooling units. Eruption units can be divided into next to crater deposits, proximal deposits, middle deposits, distal deposits and marginal deposits horizontally and their composition, grain size, thickness and degree of welding change systematically. Vertically, the pumice flow also have different phases. From bottom to top, there is plinian air fall deposits, ground surge deposits, pyroclastic flow deposits, ash cloud deposits and air fall pumice deposits. At different cross sections the sequence changed a lot. When it is next to the crater, the bottom plinian air fall deposits are not stable, while the top is post air fall pumice deposits. Proximal deposits do not have clear contacts within them. And there is no ground surge, ash cloud surge and air fall pumice deposits. What is totally different with the phase model created by Wright et al., 1980 is that proximal deposits are thin, and the the middle deposits are the thickest and have the whole different phases, well developed ignimbrite, and clear flow and cooling units. Ground surge deposits mostly occur at middle and distal deposits. Ash cloud deposits only occur at the distal part of the pumice flow.

*2. Base Surge*

Base surge is a thin turbulent. Based on different origins, there are three types of base surge: ground surge, ash cloud surge and base surge. The first two are associated with magmatic pumice flow and they are dry and distributed locally. Base surge is wet surge and it distributed on a much broader area and it can be occurring as a layer in sedimentary stratigraphy and can also form a single volcano by itself like the maar volcano. Base surges are products of phreatic and preamagmatic eruptions. In China, it broadly developed in Leizhou peninsula, Long Gang, A'er Shan, Xilinhot Quaternary volcanic area (Bai et al., 2006; Zhao et al., 2008). Most of them formed maar volcanoes which has a concentric circular surface view and have diameters usually less than 4 km. Vertical deposition phase change is complicated. There are multi cycles and they are rhythmatically repeat. Within each cycle, the bottom is composed of coarse grains interlayered with some fine grains. Parallel bedding and low angle cross bedding are well developed in the bottom. The top is full of fine grained layers with some lens of coarse grained blocks. Low angle cross bedding and lowcast and flame structures are well developed. Horizontally, the profile of the volcano show a asymmetrical gaussian curve shape. The inner wall of the crater is quite steep while the outer wall change from very steep to very gentle very fast when it is getting far away. The deposit layers of the inner crater wall dip toward the center of the crater and are very steep with angles of 30º-40º and these layers are thin and coarse grained and with well developed parallel bedding. The rim of the crater is the thickest part and very gentle. The outer slope of the crater dips toward the outside of the volcano with angles of about 0º-20º. Main structures include low angle cross bedding, mound shape cross bedding and lowcast structures. When it is getting away from the cone, the dipping is getting almost horizontal until it disappears. The front is very thin of tens of centimeters and highly controlled by the local topography. Because base surge deposits are very similar to flow deposits in the rivers and streams, it is usually hard to distinguish it from the sedimentary origin deposits. We have made great progress on how to distinguish these two deposits recently.

*3. Lahar*

Lahar is formed when the lose materials were soaked with water and driven by the eruption to flow down the slope like a landslide. Compared to the normal landslide, lahar has a lot higher temperature and it is density flow and one of the most severe volcanic hazards. Nie et al., 2009 studied the lahar in Chang Bai Mtn. They divided the lahar into different units. From proximal to distal, there are lahar clastic phase, transition phase, and super-rich phase. Clastic phase is within 64 km from the crater, clasts weighted about 80% of the whole lahar, and occupy about 60% in volume. Grain size is very heterogeneous and it contains some big boulders of 1-2.5m in diameter. Pumice concentrated somewhere to form lenses and bedding is not well developed at all. Transitional phase is located between 64-83 km away from the crater. Bedding is well developed in this phase and vertically it can be divided into different units. Grain sizes are between 10-60 cm. Super rich phase distributed beyond 83 km away from the crater. Clasts weighted 40-80% and are about 20-30% in volume. Volcanic sand and pumice are interlayered and generally developed parallel bedding and locally reverse bedding.

## VI. SUBDIVISION OF AIR FALL DEPOSIT

This research is focusing on the origin of the different subdivisions of air fall deposit. For example, now we divided it into air fall and spatter deposits, which is important to the evaluation of volcanic hazards and prediction. Spatter deposit is the product of eruption of less fragmented mamga. Lava fountain was formed during eruptions. The products are very hot and ductile and spattered on the rim of the fountain, and quickly cool down to form spatter cone or rampart. Most blocks are ductile or semi-ductile volcanic bombs and lava blocks. Because the spatter clasts are very hot, they are usually welded to each other. Vertically, they can show symmetrical or asymmetrical phase pattern. When it is extremely highly welded it looks like a lava flow. Recently, many spatter cones were recognized in east China Holocene volcanic clusters. The spatter cones also contain a lot of mantle xenoliths which can give us information about the magma source in the mantle (Fan et al., 2008; Yu et al., 2006). Air fall deposits formed when the materials are transported by wind and finally fall on the ground due to gravity. Subdivisions include: 1. Eruption column air fall deposits: acidic or intermediate-acidic volcanic clasts were carried up by the eruption column until they reach the spreading area and then spread out horizontally and then finally fall on the fround due to gravity. They form broadly distributed tuff. Thickness is not controlled by the local topography and the thickness is quite constant. Peak thickness is at about 1/3 away from the crater; 2. Co-ignimbrite ash air-fall deposit: Volcanic ash has two main sources. One is the horizontal transported materials on the top of the eruption column, the second is fine grained materials that escaped from from the pumice flow. They deposit on the top of the pumice flow as layers with very thin thickness and they are rick of glassy fragments. Vertical variance is not obvious and horizontally, they mostly deposited farther away from the crater; 3. Scoria air fall: Scoria air fall is the product of strombolian and sub-plinian eruptions and the composition of scoria air fall is quite homogeneous, and mostly are mafic. The deposit forms fallout scoria cones or fallout sheet. Fallout sheet are mostly ellipsis or fan shape and it is getting thinner when it is far away from the crater. The clasts are mainly lapilli, volcanic sand and ash. Grain sizes become smaller when it is getting far away from the crater. Next to the crater we can usually find well developed graded bedding while when it is getting farther away the bedding is not that obvious. Many of the east China Holocene volcanoes have scoria air fall deposits. For example, the "alchemy furnace" volcano in Wulanhada, inner Mongolia. It has a scoria air fall cone which is composed of coarse grained black scoria and dark grey medium grained scoria interlayered rhythmetically. During the explosive eruptions, eruption column formed above the crater, and clastic materials in the eruption column are transported by wind the fall off due to gravity to form broadly distributed air fall sheet. For instances, Jinlongdingzi volcano, Yan

Shan volcano, and Ma'an Shan volcano. The area of the air fall sheet more than 1 cm thick from Jinlongdingzi volcano is about 180 $km^2$. If we skip the the part of the sheet with less than 1 cm thick and the really fine ash floated away, the estimate volume of the sheet would be 0.07 km3. This sheet is a fan shape facing toward east which indicated the wind direction at that time.

## VII. VOLCANIC ACTIVITY AND NEW TECTONIC EVENTS

Volcanic activities provide us numerous information about the deep Earth. Holocene volcanic activities are the great expression of the simultaneous tectonic events. Most of these volcanic activities are related to the intraplate hot spot or extension environment or indirectly related to collision and subduction. Many Holocene volcanoes are located at the proper tectonic environment for volcanic activities. For example, multi-stage volcanic activities at A'er Jin fault systems are the best expression of the structures feature below the surface of the Earth (Li et al., 2006). There is a Holocene volcanic cluster at the curve of the A'er Jin fault system and Holocene volcanoes are located at the extesional shear zone, and the volcanic activities represent the fault activities in Holocene. Tengchong volcanic cluster is located at the intersection of Yaluzangbu River which formed by the collision between Indian plate and Eurasia plate. Active Holocene volcanoes are Heikong Shan volcano, Ma'an Shan volcano, Daying Shan volcano, Laoguipo volcano etc. Hydrothermal activities are quite active in the volcanic cluster area (Xu, 2006) which indicates that tectonic activities in this area are still very active too. Holocene volcanoes in Wulanhada, Inner Mongolia, also distributed along basement faults (Bai et al., 2008). The distribution of these volcanoes provide important evidence for the study of the new tectonic activities of the southern margin of Inner Mongolia plateau. The distribution of different volcanic clusters represent the regional tectonic activities. For example, Eastern China NE Datong-Da Xing'anling volcanic belt has Holocene volcanoes. From north to south, there are Bila River Ma'an Shan volcano, A'er Shan-Chai He Yan Shan, Xilinhot Gezi Shan, Wulanhada Liandanlu volcano, Datong volcanic cluster. They are all tephritic basalt. The distribution and the rock type tell us the this volcanic belt is located at the beginning stage of continental rift.

## VIII. VOLCANIC RESOURCES, ENVIRONMENT AND VOLCANIC HAZARDS

Another hot topic of volcanology is about resources, environment and hazards. China has wealthy volcanic resources like high quality construction materials, hot springs, volcanic morphology scenic spots. Right now China has set up volcanic geologic park as Wudalianchi, Jingpo Lake, Longgang, A'er Shan, Leiqiong peninsula, Tengchong, and Weizhou Island to protect these volcanic resources. Newly discovered volcanoes are also in processes of being pretected. Recently, except for the continuing research on the volcanic hazards prediction on Chang Bai Mtn Tian Chi volcano, WudalianChi, Ma'an Shan volcano, and Tengchong volcanic cluster, we started the same kind of research in Longgang, Wulanhada etc. Based on historic eruption records, we made hazards possibility maps and did some preliminary prediction and evaluation of possible future eruptions.

The harmonic development of resources, environment, hazards, human being is the most important task in from of all geologists, and volcanology is one of the most important fields. This paper briefly reviewed the main progress in volcanology in China. What we have not summaried in this paper will be addressed by other authors in the future.

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# RECENT PROGRESS IN ACTIVE VOCLANOES IN CHINA

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In the last two decades great progresses have been achieved in active volcanoes in China. The first program on exploration and monitoring active volcanoes in China started in 1995, and then a series programs have been excuted. At first, Holocene active volcanoes, especially Tianchi volcano, Wudalianchi volcano and Tengchong volcano, attracted much more studies. Geology, petrology and chronology of these volcanoes have been studied, long time monitoring and associated instruments have been build up. Tianchi volcano, as the most dangerous volcanoes, have been recognized both scientific and public. However, there are much more Quaternary active volcanoes, caused by plate motion of Tibeat and Pacific plate, than Holocene active volcanoes in China. In the 21st centrury these studies have been extended to the Quaternary active volcanoes. This paper summarizes recent progresses both on Holocene and Quaternary active volcanoes.

## I. MECHANISM OF EXPLOSIVE ERUPTION AND MAGMA MIXING OF TIANCHI VOLCANO

Dynamic evolution of the two magma chambers, in mantel and crust separately, makes the Tianchi volcano active for a long time. Geophisical explorations, as well as other researches on geology and geocchemistry, reveal that two magma chambers, in mantle and crust seperately, lay beneath support the Quaternary erutions of the Tianchi Volcano (Liu et al., 1998; Fan et al., 2006; Tang et al., 2006). Manttle derived trachybasaltic magmas continuously flux to the crust magma chamber in ~1 Ma, and then evolve to the felsic magmas and erupt. These eruptions make the large cone of the Tianchi Volcano.

Magma mixing triggers the Millennium eruption, one of the biggest eruptions in the world in the past 2000 years, of the Tianchi Volcano. Some petrological characteristics provide evidences of magma mixing: (1) blocks and fine twisted-bands of trachybasaltic magma debris distribute in the grey pumice (main products of the Millennium eruption); (2) fayalite coexists with quartz in the grey pumice, which suggests that the magma is not in balance; (3) erosions occur in most of the phenocrysts. The story may be that the basaltic magma with high temperature (1100-1200℃) injects to the rhyolitic magma with lower temperature (850-900℃) in the crust, then convection occurs in the crustal magma chamber. This process overheats the crustal magma chamber to explosive eruption, and the petrological characteristics records the process of magma mixing (Fan et al., 2005, 2006, 2007). Chronological evidences (Fan et al., 2007) indicate that the cone-forming state, mainly controlled by evolution of the crustal magma chamber, last from ~1Ma to 0.04 Ma. However, in this period of time, some trachybasaltic eruptions direct from mantle magma chamber occur in 0.87Ma-0.06Ma, and form several small volcanic cones on the main cone of the Tianchi Volcano. Magma mixing and interactive evolution between the two magma chambers in the mantle and crust is a significant characteristic of the Tianchi Volcano. Subduction of the Pacific plate and the subsequent back-arc extension provide the tectonic background and potential mechanism of magma genesis.

U-series disequilibrium provides estimation of the lifetime of magma chamber. Sui et al. (2006)

built up a new mathematic model describe the processes of crystallization and U-Th decay in magma chamber, gave an alternative interpretation to the popular mineral U-Th isochron. This new model revealed that the time scale of magma residence and crystallization of the Millennium eruption was about 100 ka. This equaled to the maximu age of Dunlap's (1996) estimation, which was 60-100 ka.

## II. HOLOCENE VOLCANOES IN JINGPOHU

The Jingpohu Volcano is located in Xiaobeihu forest center, Ning'an county, Heilongjiang Province. Volcanic lavas and breccias cover an area of ca. 500 $km^2$, and explosive eruptions from 5200 BPa to 5500 BPa make over ten volcanic cones in 300 years (Zhang et al., 2000; Fan et al.，2003). Holocene eruptions produce a potassic series rocks, including potassic trachybasalt, basanite and phonolitic alkaline basalt (Fan et al., 2006). Goechemical evidences suggest that these potassic magma series derive from different mantle sources, were not evolved from a common mantle source by fractional crystallization.

The western part of the Jingpohu Volcano is composed by trachybasalt and basanite, both from mantle sources with slightly potassic metasomatism. The trachybasalt is produced by partial melting of high percent, while the basanite by that of low percent. Products in the eastern part of the Jingpohu Volcano generate from the mantle source with intensive potassic metasomatism. These volcanic rocks contain mantle xenoliths and phenocrysts of leucite, phlogopite and amphibole. Augite megacryst reveals that the pressure of magma chamber is 1.57-1.63 GPa , and then suggests that fractional crystallization of the phonolitic tephrite magma occurs in ca. 52-54 km.

Researches indicate that the Jingpohu Volcano is located in the belt of back-arc extension caused by the subduction of the western Pacific plate. Dehydration of the subducted plate and mantle wedge cause varous potassic metasomatism and partial melting in the mantle source. This forms the mantle heterogeneity in the small scale of 15 km in Jingpohu Volcano, and produces various series of magmas.

## III. QUATERNARY VOLCANOES IN DA HINGGAN LING MOUNTAINS

The Quaternary volcanoes of the Da Hinggan Ling Mountains is divided into two parts: Halaha River and Chaoer River volcanoes (HC for short) in the south, and Nuomin River and Kuile River volcanoes (NK for short) in the north. 35 Quaternary volcanoes and ca 400 $km^2$ lavas distributed along a Quaternary NE strike belt in HC. 24 Quaternary volcanoes and ca 600$km^2$ lava flows were emplaced in NK. Based on studies on the volcano stratigraphy, in conjunction with weathering extent and geological dating, it is identified that the volcanism occurred in 4 periods: Early Pleistocene, Middle Pleistocene, Late Pleistocene and Holocene(Zhao et al., 2008, 2010; Bai et al., 2005). Gaoshan volcano and Yanhshan volcano in HC, along with Maanhsan volcano in NK is determined to be Holocene volcanoes. Four eruption types-Strombolian type, Gaoshan-Yanshan type, Hawaiian type, and Phreatomagmatic type, are identified. Studies on geochemistry indicates that volcanic rocks HC are Na-series alkali-basalts, while basalts in NK belongs to K-series.

Spinel bearing peridotite and garnet bearing peridotite are widepread in the xenolith in HC and NK. Geothermometer and geobarometer reveals that garnet bearing lherzolite in Chaoer river have a pressure and temperature equilibrium at about 1164℃ and 2.36 GPa(depth at 76km). This is resemble other garnet bearing four phase lherzolite in eastern China, but differentiate them from 5-phase-coexist lherzolite. It could be soundly inferred that these xenolith came from a certain depth which is lower than the phase transition zone(>70km)(Fan et al., 2008).

## IV. HOLOCENE VOLCANOES IN WULANHADA

About 30 volcanoes are distributed in the Quaternary volcano cluster of Wulanhada with lava flows covering an area about 280km$^2$, which is located in the southern sector of the Da Hinggan Ling Mountains-Datong volcanic active belt. The volcano cluster overlies the Archean Wulashan Rock Group and Neogene basalt. Most of cones built by basaltic agglutinate and clastogenic lava have been denuded to some extent though most of vents still remain the basic form. Based on studies on the volcanic field stratigraphy and volcanic topography, in conjunction with weathering extent and geological dating, it is identified that about volcanoes begins to erupt since 30ka ago, and volcanic activity can be divided into both the Late Pleistocene and the Holocene epochs. The cones formed in Late Pleistocene are relatively smaller in size and experienced denudation in a certain extent. Holocene volcanoes have intact volcanic edifices, including cones, vents, lava domes, lava units and lava structures such as inflation cracks, lava tumuli. Lava flows obstructed the drainage, by which formed volcanic dammed lakes such as Moshigainao and Wulanhushaobai. Quaternary volcano cluster of Wulanhada is the only one which once erupted in Holocene in the southern border of the Mongolian Plateau, is a natural “volcano museum”, and is a window to research the deeper structure and activity of the modern crust in this area.

## V. HOLOCENE VOLCANOES IN NORTH HAINAN ISLAND AND LEIZHOU PENINSULA

Hundreds of volcanoes and ca 7000 km$^2$ volcanic rocks are emplaced in North Hainan Island and Leizhou Peninsula, the largest Quaternary volcanic field in the South China. Volcanic activities happened since Eocene, and some volcanoes even erupted in Holocene. Based on researches on volcanology and geological features, in conjunction with geological dating, it is identified that Leihuling volcano and Maanling volcano erupted in Holocene(Fan et al., 2004). Olivine-tholeiitic basalt in Leihuling represents relatively primary magma, while quartz-tholeitic basalt in Maanling volcano is more evolved products.

According to Fan et al.(2006), Weizhou island and Xieyang island, 20km south of Beihai city, are volcanic genesis. Volcanism in early Pleistocene caused violently phreatomagmatic eruptions and created the two islands. OSL and Shell $^{14}$C dating indicates that the latest volcanic eruptions happened about 30ka ago（36ka-33ka）.

## VI. TENGCHONG VOLCANOES

Tengchong volcanoes are situated in the northeast of India-Eurasia collision zone. Tens of volcanoes and ca 9000km$^2$ volcanic rock, mainly formed in Quaternary, are located in the Tengchong basin in the north of Teng-Liang graben. Maanshan volcano, Dayingshan volcano and Heikongshan volcano are the most well-preserved among those volcanoes, and topographic features and geological dating(Xia et al., 1995; Wang et al., 1999)indicates that they are products of the latest volcanic eruptions in Tengchong. Studies on geochemistry reveals that magmas of the three volcanoes have similar petrogenesis and evolve trends(Fan et al., 1999). It is thought that the magma source of Tengchong volcanoes is the mixture of mid-ocean ridge basalts(MORB) and enriched mantle. It is deduced that the Neotethys subducted ocean crust refused, hence volcanoes were activated with high potassium calc-alkaline magma. This explain why volcanic rocks with characteristics of volcanoes at island arcs or active continental margins expose at the tectonic settings of intra-plate. The magma of Maanshan, Dayingshan and Heikongshan endure crystal fractionation of pyroxene and ilmenite at the chamber stage and plagioclase fractionation at the ascending stage, which induced the magma evolving, from intermediate-basic magma to intermediate-acidic magma, and lava evolving by the course of basaltic trachyandesite- trachyandesite-trachydacite(Zhao et al., 2010).

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# THE ACTIVE LEVEL ANALYSIS OF CHANGBAISHAN VOLCANO

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ABSTRACT: The monitoring work of Tianchi volcano started in 1985.We do seismic monitoring work from July to September every year. From 1985 to 1994,we recorded about 40 volcanic seismic events every year. The number of volcanic seismic events came into being increased obviously since July, 2002.There occurred 1293 seismic events in 2002. In 2004, though the number of seismic events decreased, but the energy releasing maintaining increasing. In recent years, the seismic activity come into increasing obviously in the vicinity of Tianchi volcano. Two tectonic earthquakes(ML4.4,ML4.0) occurred in Fusong town,where 30 kilometers away from Tianchi volcano In December,2004 and April,2005. In the same time, many earthquakes and volcanic seismic events occurred in the vicinity of Tianchi caldera .People could perceive some of these earthquakes and earthquake sounds could be heard and slightly earthquake destruction happened. After August,2005, the seismic activity decreased smoothly and returned to the level of 2002.

"Some active volcano monitoring and research in China" program was started in 1997 and Mr Liu Ruoxing take charge of this work. This program brought Chinese active volcano monitoring and research work into a new stage. Changbaishan Tianchi volcano observatory(TVO) was set up and taken into use in 1999.They started seismic and landform deformation and GPS and level line and fluid geochemistry measurements. Changbaishan volcano monitoring center was set up in Erdaobaihe, where located in the north slope of Changbai mountain in 2006. The new volcano seismic monitoring center was built. The GPS network was enhanced. A new level line route was built in the west slope of Changbai mountain. Geoelectricity and relative gravitational measurements was built as well.

In this paper, we analyzed the monitoring ability of Changbaishan volcanic seismic monitoring and analyzed the volcano active level of Changbaishan in recent years from the fundamental monitoring results. We also did the elemental analysis of the active level nowadays in Changbai mountain.

## I. VOLCANIC SEISMIC MONITORING

### *1. Seismic Network*

The Tianchi volcano observation(TVO) was set up in July,1999. There was a permanent seismic station and 5 temporary seismic stations including Shuangmufeng (SMF), Weidongtai(WDT), DongDapo(DDP) and Xidapo(XDP) station at the beginning. They did this work from July to September every year and save the data with a hard disk. They got the data from the station periodly.

In order to strengthen the control of micro-seismic events in the volcanic area, the seismic network was rebuilt and expanded during the tenth five year plan. A new seismic monitoring center was built in Erdaobaihe which includeing five new seismic stations. ZXT, SMT,SMF used the under well short period seismometers and other stations used broad-band seismometers. New seismic houses were built in all the seismic stations.

CBS station use CTS-1E broad-band seismometer. SMT, ZXT and SMF station use FSS-3DBH short period seismometers. DDP, XDP and WDT use CMG-3ESP broad-band seismometers. HST, QXZ,CBT and MJT use BBVS-60 broad-band seismometer. CBS station use EDAS24-L6 data collecting meter and other stations use EDAS-24IP data collecting meters.

According to the special geographical environment, the stations were distributed in appropriate locations. The new Changbaishan volcano center was built in a highland where 40 kilometers away from the magma vent to protect the safety of workers and instruments when the volcano erupts in future. This highland hasn't been destroyed by pyroclastic flow or lahar historically.

5 seismo-stations including CBS, WDT, QXZ, DDP and XDP were distributed in the range of 1-15 kilometers away from the magma vent.

2 seismo-stations including SMT and SMF were distributed in 15-25 kilometers away from the magma vent.

4 seismo-stations including HST, ZXT, MJT and CBT were distributed in 25-50kilometers away from the magma vent. Figure 1.1 is the distribution map of the seismic network.

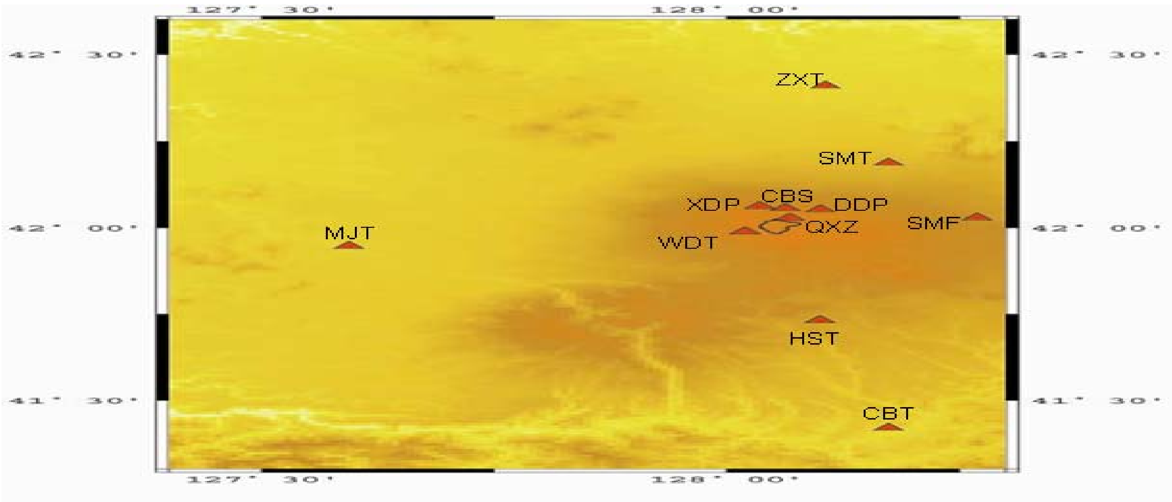



Fig. 1.1 The distribution of seismic network of Changshan volcano observatory

All the seismo-stations were unmanned digital stations and acquired the continuously seismic data of the Tianchi volcano. Cable transmissions, wireless transmissions and hard disk storages were adopped to get the data from the stations to complete fast earthquake location and other data analysis. Cable transmission were carried out by SMT, CBS, CBT and MJT, other stations still use hard disk to save the data.

The new seismic center can detect ML 0.1 volcanic events and give the detail location of ML 1.0 or larger volcanic events. Thus, it can monitors volcanic events in the range of 50 kilometers around the magma vent.

## 2. *Time Characteristic of the Volcanic Events*

Since the set up of TVO in 1999, till the middle of 2002, the number of seismic event remained an averaged background of several dozens. The seismic number increased sharply from June, 2002. The total number of the seismic activity in 2002 was 470, in 2003 1293, in 2004 728, in 2005 567, in 2006 118, in 2007 101, in 2008 80 ,in 2009 87,in 2010 till the end of June 52. In a time sequence from 2001 to 2010, the maximum magnitude of the seismic events listed as Ml 2.2, 3.0, 3.7, 4.4, 4.0, 2.8, 1.8,1.6,1.5 and 1.1. Respectively among which the Ml 4.4 and 4.0 earthquake belonged to the normal tectonic earthquakes outside of the Tianchi Volcano. Figure 1.2 presents the M-T distribution of the seism. It is easily recognized out that the seismic level increased gradually since July 2002. The monthly number of the seismic activity uprised from dozens to hundreds with a peak annual number of 1293 in 2003. Then the number declined till 2005 and resumed the background level same as in 1999-2001.

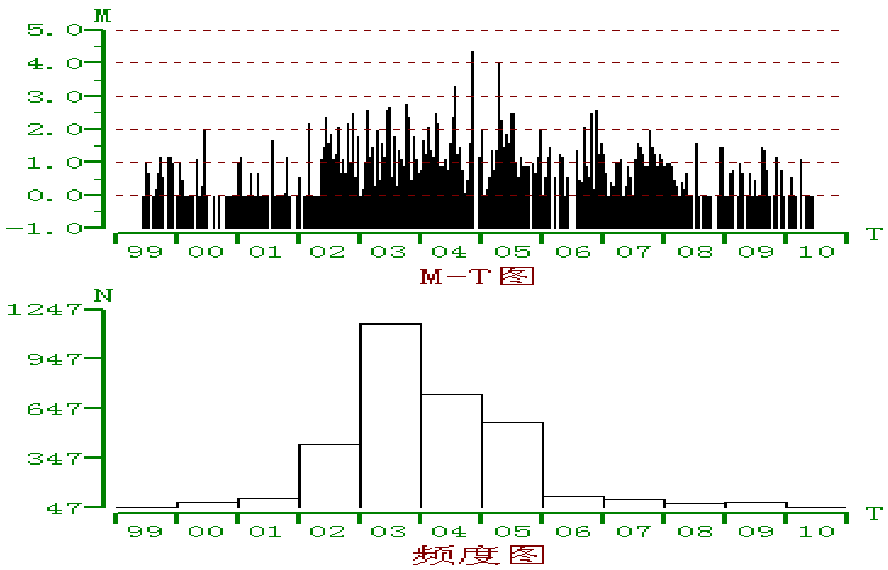



Fig 1.2 M-T distribution of volcanic events from 1999-2010

From a permanent receiver at the Changbaishan Station (CBS), located near the center of the volcano (1.5 km from the north caldera rim), a continuously seismic data has been got that made the basement for the frequency and magnitude discussion in the next paragraphs. There happened 83 earthquakes magnitude over 1, 17 over 2, and 1 over 3 in 2002. In 2003, 15 earthquake swarms took place. On September 8, 2004 a maximate earthquake swarm happened at the Tianchi Volcano since the TVO had been set. The swarms lasted for about 4 h with 51 earthquakes together, in which 12 over Ml 1, 3 over Ml 2 and a maximum Ml 3.7. Ground sounds were heard from the 3 earthquakes over Ml 2 with a very big sound after the Ml 3.7 earthquake. People at the north and west part of the volcano could feel the shake of the Ml 3.7 earthquake. Fractures appeared at few constructions in the Changbai Canyon. A waveform recorded at CBS is shown in Figue 1.3.

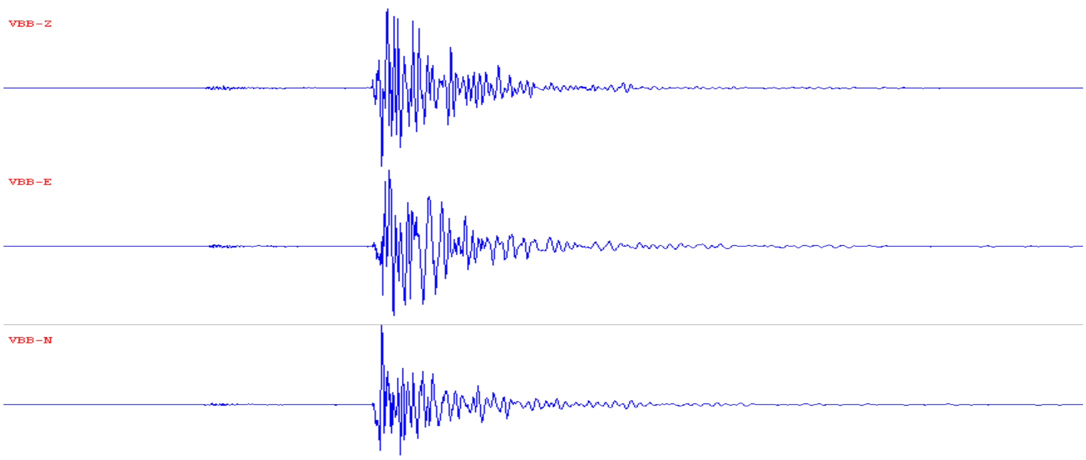



Fig .1.3 Waveform of the largest Ml 3.7 earthquake between 2002 and 2004

It can be separated into 3 parts in the TVO moniting history since 1999, that is, from 1999 to June 2002 a background, from July 2002 to July 2005 a peak, and from Augest 2005 to presence a recovered. The seismic activity was low in the first period. The monthly number of seism remains at below dozens with a maximum Ml 1.5 earthquake. The number of seism increased obviously in the second period, started from July 2002, accompanied with series of swarms. The daily number of seism rose upto over a hundred. The biggest magnitude of the earthquakes happened in this period was Ml 3.7 on September 8, 2002. Near the end of 2002, after the two tectonic earthquakes Ml 4.4 and 4.0 happened, southwest of the Tianchi Volcano, on the north flank of the Wangtiane Volcano, the seismic active level went down obviously. Till the end of 2005, the level of seismic activity returned to the background level as same as before the July 2002 (Liu et al. 2006).

The same as other earthquakes occurred in other active volcanoes, the seismic activity in Tianchi volcano often come in swarms as well. For example, there happened many earthquake swarms during 2002-2003, hundreds of seismic events can be recorded in one day some times.

### 3. *Localized Hypocenters of the Earthquakes*

There was no data on the hypocenter location of the earthquakes surrounding the Tianchi Volcano because the lack of seismic activity and the seasonly monitoring station before 2001. It was recorded from the CBS station that there existed an arriving-time-difference about 0.8 s for the P and S wave of the earthquakes. So the distance between the CSB station and the hypocenter of the earthquakes was within 5 km. Since the set up of a mobile seismic net work monitoring the Tianchi Volcano in 2002 the increased intensity of the network improved the localizing ability of the earthquakes. The hypocenter and depth distribution of the seismic activity since 2002 was shown in Fig. 1.4 (Wu *et al.* 2005).

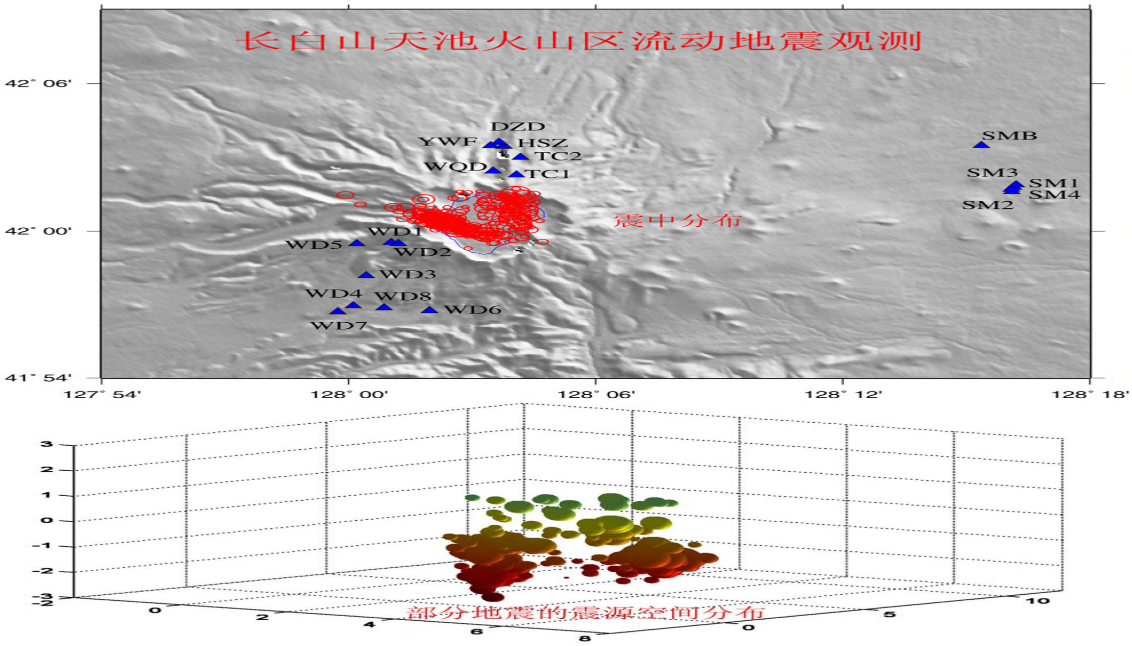



Fig. 1.4 Hypercenter and depth distribution of earthquakes surrounding the Tianchi Volcano

It was inferred that the earthquakes focused mainly on within or near the caldera of the Tianchi Volcano at a distance of less than 3 km from caldera rim and a depth of mostly less than 5 km below the caldera rim. There happened several sensible earthquakes, mostly less than Ml 2-3, surrounding the Tianchi Volcano since 2002. The high level of sensibility of these earthquakes was related to the shallow depth location of the earthquakes. It can be inrerred from Fig. 1.4 that there exists a belt of concentrated hypercenters of the earthquakes in NW and NNW direction.

According the genetic and frequency features of the volcanic earthquakes, it can be grouped into 4 types, that is, the tectonic, hybrid, long period and tremor event.

The genetic of tectonic events is similar to common tectonic earthquakes. It usually occurred in volcanic area caused by the tectonic activity of the crust. Its P wave and S wave can be distinguished easily and its prominent frequency is short period wave. This kind of volcanic event is also called A type event.

Long period event is waveform that caused by underground stress or temperature grad or magma activity or other fluid movement. Its characteristic is P-wave sharp, no S-wave. Its period is 1-5 Hz,longer than tectonic events obviously(Wu tec.2005).This kind of volcanic event is also called B type event.

The hybrid volcanic event is secondarily triggered earthquake. The first earthquake reach the surface and be received(short period wave),and the wave spread down triggers the magma which is deeper than the hypocenter, it cause the hot fluid activity. The seismic wave (long period) caused by the fluid reach the surface and be received by the receiver.This kind of event is infrequent.

The tremor is caused by the magma movement absolutely and its duration time is long, often several hours or several months. The prominent frequency of tremor is long period waveform, some small tectonic like waves can also be found in the waveform. The tremor is one of the most important signal before a volcano eruption. The nearer the time to eruption, the longer the duration time of the tremor. But not all the eruption tremors can indicate a new eruption.

From the classification of volcanic events above, we can see that it is very important to research the earthquake type in order to judge a volcano’s active level. It is commonly recognized that long period event and tremor are connected with magma or hot fluid movement and these earthquakes’ frequency are 1-5 Hz.

Study from the frequency distribution of the typical volcanic earthquakes of the Tianchi Volcano between 2002 and 2005 indicates that all the main frequency of the earthquakes basically falls down 5-8 Hz (Fig. 1.5). These events belong to tectonic events induced from the shallow localized fracture because of the deep activity.

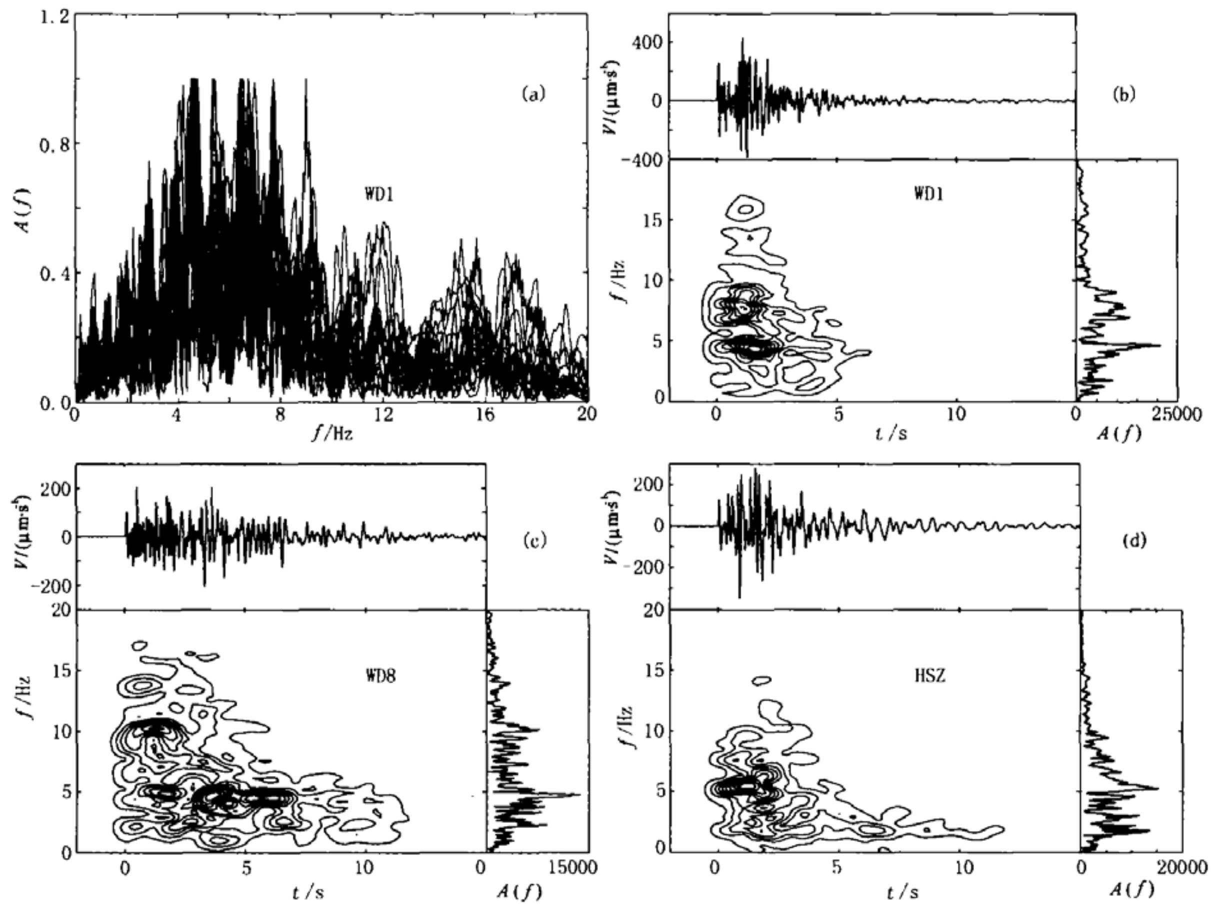


Fig. 1.5 Typical frequency distribution of the volcanic earthquakes in the Changbaishan area

## II. LANDFORM DEFORMATION

The landform deformation in TVO includes permanent deformation survey in a cave, level line and GPS survey. The instrument in the cave include DSQ water pipe meter, SSY－III stain gauge and PET tidal gravity meter. The baseline in east-west direction is 10.5m and 12m in south-north direction. The level line survey in Changbaishan has been started since 2002. There was a level line route in the north slope which is 24.8km. The average occasionally error in 1 kilo is 0.13mm. it meets the first-class level line criterion. This level line route observed large abnormal variety from 2002 to 2003. The elevation of the whole route(24.8km) uprised 38.6mm. The GPS network is consisted by 16 points, it can detect changes in 500km2 and the instrument is 350 double frequency receiver. The level line and GPS survey are done one time every year.

### *1. GPS Horizontal Displacements in Tianchi Volcano*

The GPS network of Changbai mountain is a midpoint polygon. The center point is located in the vicinity of TVO and other points located around it equably. The average border line of the network is 15Km long. The shortest line is 8.65Km, the longest line is 23.99Km. The range of the network is 800 km2. The new network was set up in the summer 2006 and before it another GPS network including 8 points was used. 9 temporary surveys were taken during 2002-2008.

The Tianchi Volcano showed a weak horizontal deformation before the summer of 2002 that was consistent with the weak verticale deformation from InSAR data between 1993 and 1998. The weak deformational feature of the Tianchi Volcano before the summer of 2002 was consistent with the lower level of seismic activeity at the same time (averaged annually dozens). It can be inferred that the Tianchi Volcano remains in a stable state before that.

At the Tianchi Volcano, the land deformational process since 2002 was similar to the sharp increase and gradual attenuation of the seismic activeity between 2002 and 2004 (Hu et al 2004). The surface deformational level of the Tianchi Volcano, an abnormal change occurred that followed an attenuation trend obviously.

The horizontal displacement mearured from GPS survey between 2000 and 2007 are respectively shown in a-f of figue 2.1 from which one can see an inflational process centered at the Tianchi Volcano after 2000. The horizontal displacement of marker P0 and P4 between 2002 and 2003 reached a maximum value of 4 cm. After 2003, the deformational rate of the Tianchi Volcano kept in a declining trend and since 2005 recovered to the quiet state as same as it between 2000-2002.

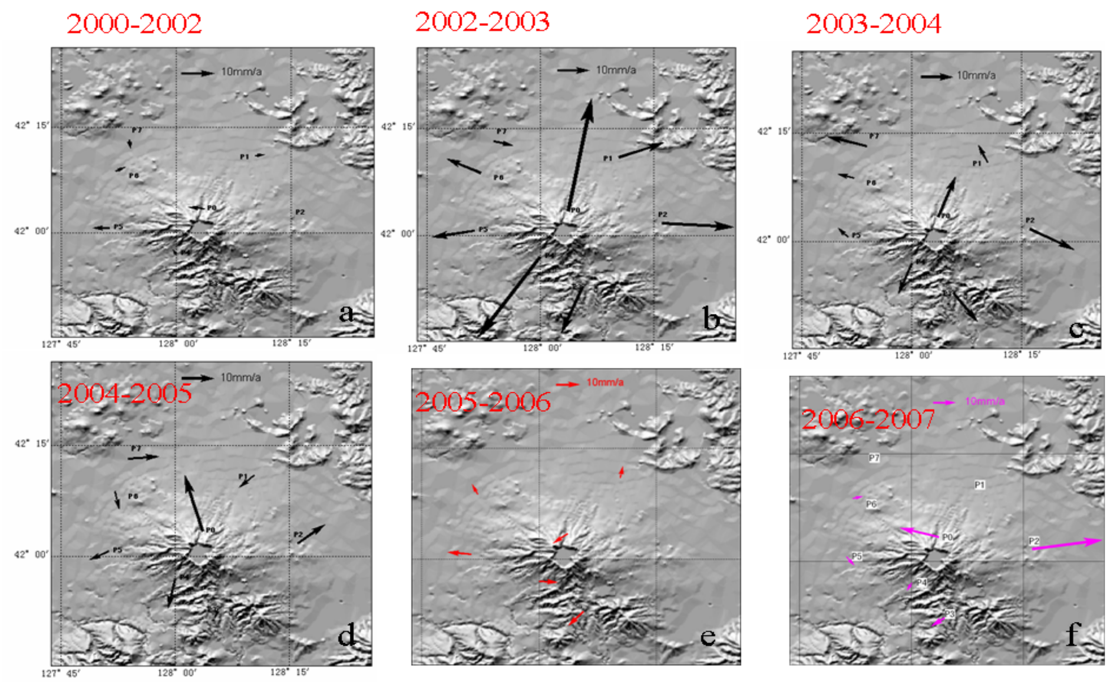



Fig. 2.1 Variable GPS displacement rate of the Tianchi Volcano

The GPS point increased to 15 from 8 since 2008. We obtained the vector variation of every GPS point from 2008 to 2009, According to the GPS calculating result(as to table 1, Fig 2.2).

Table 1. The vector variation of GPS points from 2008 to 2009

| Long. | Lat. | E & N Rate | | E & N Adj. | | E & N +- | | RHO | H Rate | H adj. | +- | SITE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (deg) | (deg) | (mm/yr) | | (mm/yr) | | (mm/yr) | | | (mm/yr) | | | |
| 128.269 | 42.029 | -1.77 | 1.08 | -1.77 | 1.08 | 13.06 | 12.60 | -0.624 | 6.89 | 6.89 | 58.71 | CBP2_GPS |
| 128.219 | 42.111 | 25.37 | -18.15 | 25.37 | -18.15 | 136.82 | 137.70 | -0.002 | 0.03 | 0.03 | 141.30 | CBN4_GPS |
| 128.197 | 42.134 | -3.85 | -1.33 | -3.85 | -1.33 | 12.70 | 11.75 | -0.683 | -78.47 | -78.47 | 24.06 | CBN3_GPS |
| 128.173 | 42.185 | 2.62 | 6.92 | 2.62 | 6.92 | 12.76 | 11.52 | -0.702 | 9.16 | 9.16 | 21.14 | CBP1_GPS |

128.130 42.140 -3.51 -1.04 -3.51 -1.04 12.59 11.37 -0.701 13.35
13.35 20.57 CBN2_GPS
128.094 41.882 -4.25 6.89 -4.25 6.89 11.73 11.22 -0.688 -6.42
-6.42 21.98 CBP3_GPS
128.089 42.099 6.91 -1.39 6.91 -1.39 12.44 11.26 -0.701 17.27
17.27 22.75 CBN1_GPS
128.061 42.057 2.94 -7.61 2.94 -7.61 12.56 11.66 -0.668 7.82
7.82 33.97 CBP0_GPS
128.019 41.992 1.18 -0.40 1.18 -0.40 11.94 10.88 -0.708 -6.74
-6.74 18.76 CBN7_GPS
128.000 41.950 -0.74 3.15 -0.74 3.15 11.86 10.89 -0.698 1.29
1.29 20.00 CBP4_GPS
127.930 41.954 -1.56 0.20 -1.56 0.20 11.86 10.73 -0.694 3.34
3.34 19.90 CBN6_GPS
127.898 42.220 0.21 -3.35 0.21 -3.35 13.13 11.27 -0.656 -50.45
-50.45 36.45 CBP7_GPS
127.869 42.146 1.19 0.65 1.19 0.65 12.58 10.72 -0.689 52.50
52.50 20.67 CBP6_GPS
127.855 42.011 -9.76 -6.54 -9.76 -6.54 12.27 10.82 -0.668 -22.26
-22.26 28.25 CBP5_GPS
127.775 42.049 -2.26 0.51 -2.26 0.51 12.53 10.95 -0.626 -47.49
-47.49 26.47 CBN5_GPS

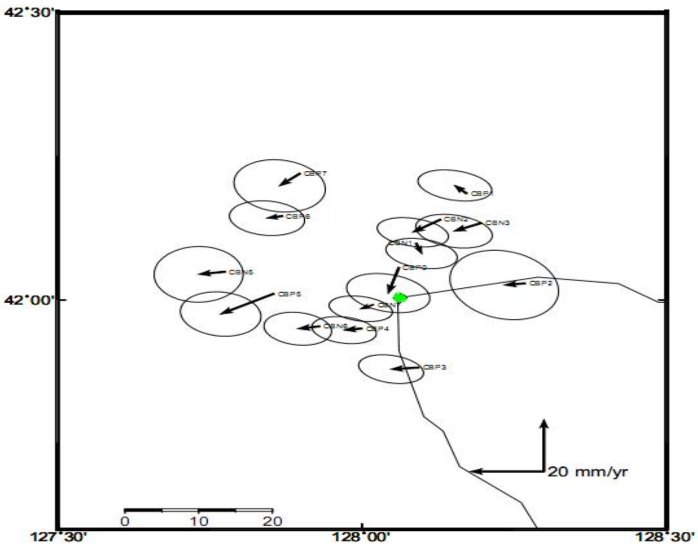



Fig 2.2 The vector variation of GPS points from 2008 to 2009

Thus we can see , the error of each point is relatively well-proportioned after deleting individual points which having bad quality of observation. The average error can be controlled in 5mm. The vector moving direction of each point has the same character compared with the results of 2008. The direction is West-South and the biggest error is not more than 9mm.

*2. Vertical Displacements in Tianchi Volcano*

Two level line route were set up in north slope and west slope by Jilin seismological bureau. The north route located between the Changbai waterfall and Huangsongpu, the total length is 24.8Km, the relative elevation difference is 901m. The west route located between Tianchi and the entrance of west slope. The total length is 30Km, the relative elevation difference is 1084m.

The levellyng survey on the north flank of the Tianchi Volcano has been processesd 8 times since 2002 and the relative variation for different times is shown in Fig. 2.2. One can see from Fig. 2.2 accumulative 68.12 mm uplift of the Tianchi Volcano between 2002 and 2005, especially between 2002 and 2003, a maximum 38.6 mm uplift measured from a 24.8 km length level line survey. After 2003 the vertical displacement rate falls down gradually but still keeps in an uplift stage. It is worth to state that the near 3 cm uplift measured between 2005 and 2006 is inconsistent with the declining trend of seismic activity at the same time. The reason for this is due to a “false displacement” because of the instrument system shift from the light water tube to electronic.

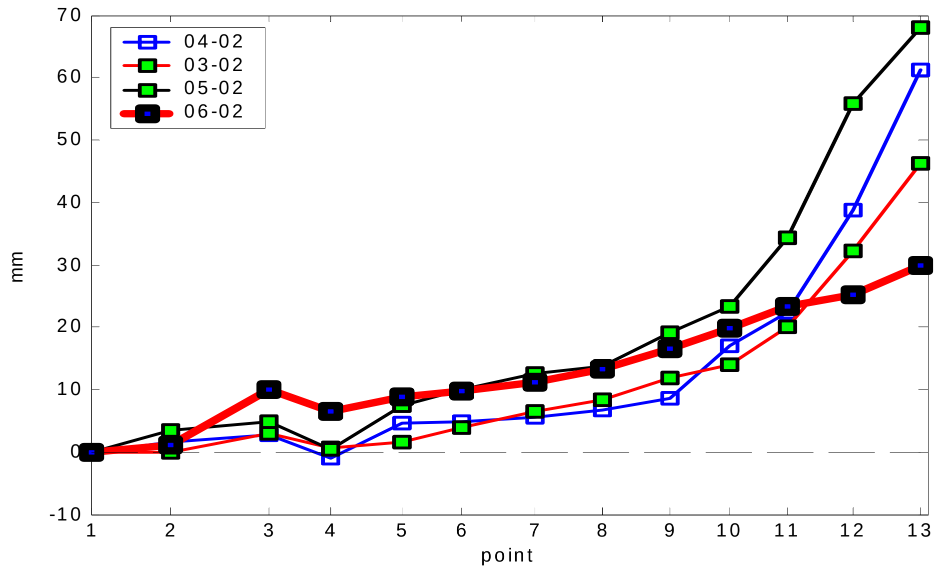



Fig. 2.3 Vertical uplift of the Tiaanchi Volcano

The new optic level line meter was used both in the north slope and the west slope in Changbaishan since 2006. The false displacement appeared after 2006 ,caused by the system error of the two level line meters. We analyzed the data after the new level line meter being used.

Table 2. The elevation and its difference of the north slope from 2006 to 2009 unit: mm

| Date | 2009 | 2008 | 2007 | 2006 |
|---|---|---|---|---|
| Elevation | 901151.70 | 901149.26 | 901148.20 | 901140.05 |
| difference | 2.44 | 1.06 | 8.15 | 0 |

Table 2. The elevation and its difference of the west slope from 2006 to 2009 unit: mm

| 日期 | 2009 | 2008 | 2007 | 2006 |
|---|---|---|---|---|
| 高程 | 1084653.77 | 1084659.21 | 1084661.54 | 1084636.2 |
| 变化量 | -5.44 | -2.33 | 25.34 | 0 |

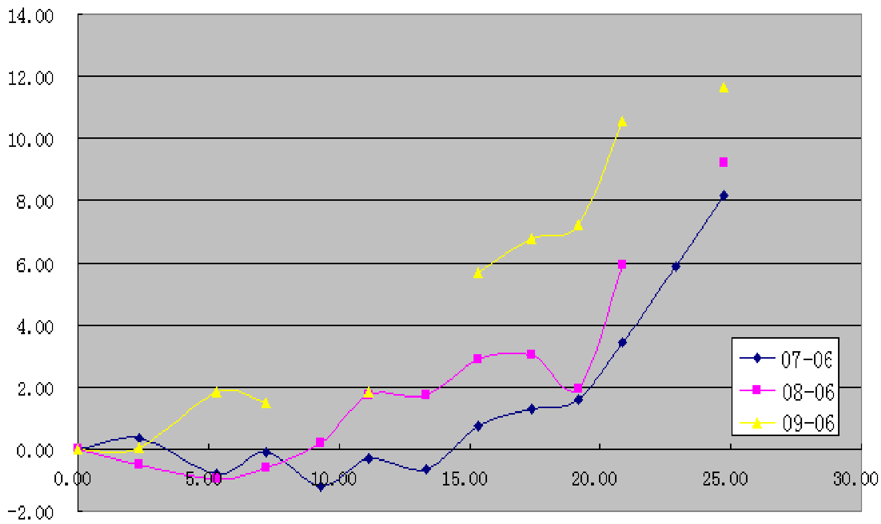



Fig 2.4 The elevation variation of the north slope from 2006 to 2009

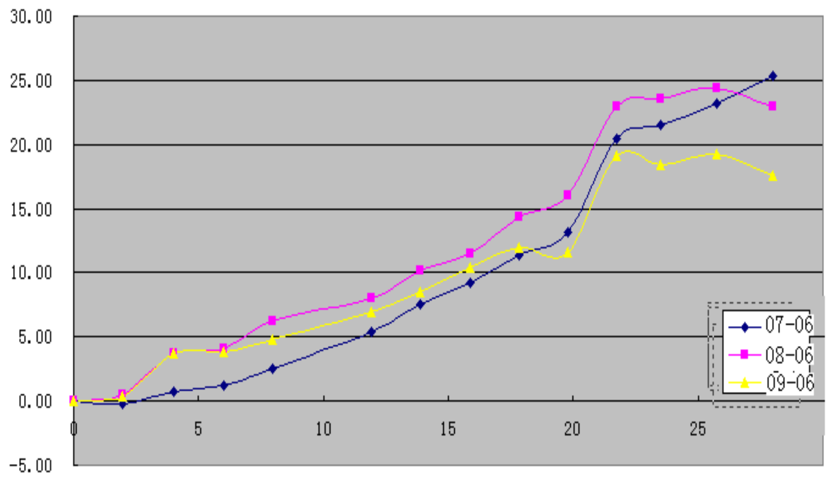



Fig 2.5 The elevation variation of the west slope from 2006 to 2009

Table 2、table 3、 Fig 2.4 and Fig 2.5 show the elevation variation from 2006 to 2009. The difference between 2008 and 2009 is relatively small both north slope and west slope, one is 2.44mm and another is -5.44mm. The elevation variation is relatively big in the west slope from 2006 to 2007, the possible reason is that the base frusta has been set up in short time and slightly up-down change maybe occurred.

There is one thing we should pay more attention , the elevation difference in the west slope is in descending state in the recent 2 years. Whether this fact can predict the crust in the west slope is in contracting stage? We still need more data to ensure it. On the other hand, though the GPS vector change slowly from 2008 to 2009, but the movement direction is in the same direction , we should also strengthen monitoring work and fundamental research work.

## III. FLUID GEOCHEMISTRY RESEARCH

The Changbaishan fluid geochemistry observation started in 1985. Temporary Rn, temperature and flux observation were carried out by Antu seismological office. Yanbian seismological bureau and Jilin seismological bureau got and analyzed the sample one time every year later until 1998. They accumulated many valuable first-hand data. The Changbaishan Volcano Observatory was set up and started observation in 1999. Periodic gas observation was carried out all the year round. The No. 8, No. 9 and No. 15 hot springs on the northern slope and the No. 1 and No.2 hot springs on the western slope of the mountain were selected for monitoring purpose. $CO_2$, $N_2$, He, $H_2$, $O_2$, $CH_4$, etc. were selected to be analyzed and the temperatures of hot springs were measured as supplementary data. Prior to June 2007, the instrument used to analyze the gases was a SQ-206 gas chromatograph. After June 2007, we began to employ a SP-3420 gas chromatograph. In recent years, some experts from the Institute of Geology, Chinese Seismology Administration have conducted sampling and carried out geothermal, gas and isotope monitoring in Changbaishan hot springs and have got many significant results. According to their studies, the ratios of $_3He/_4He$ were analyzed, thus providing the important scientific basis for further geothermal monitoring and research in the Changbaishan Mountain region.

Isotope geochemical characteristics of gases can be used to develop the information about the origin of the gases in the volcanic area. First of all, the origin of volcanic gases can be constrained in terms of the ratio of $_3He/_4He$. The ratio of $_3He/_4He$ is the most effective index to constrain the origin of gases, as is commonly accepted throughout the world and it has a relatively stable range in the atmosphere, crust and mantle. Usually, the ratio of $_3He/_4He$ in the atmosphere is $1.4\times10^{-6}$ (Wang Xianbin, 1989); The ratio of $_3He/_4He$ in gases from the crust is $2.0\times10^{-8}$; the ratio of 3He/4He in gases from the mantle is $1.1\times10^{-5}$–$1.4\times10^{-5}$. According to the isotope data provided by Shangguan Zhiguan et al. (1998), the ratio of $_3He/_4He$ from the Changbaishan spring area is very similar to that from the Jinjiang spring area. The ratio is within the range of $7.51\times10^{-6}$–$8.24\times10^{-6}$ , with an average value being 5.61 times that of the air (5.61 Ra). It is generally believed that when $_3He/_4He$ (R) in a sample exceeds $_3He/_4He$ (Ra) in the atmosphere, it can be concluded that mantle-source He must have been involved. Obviously, the $_3He/_4He$ ratios in hot spring samples colleted in the Tianchi volcanic area are much higher than Ra, so the gases obtained from the Tianchi volcanic area are believed to have been derived from the mantle, at least the main elements came from the mantle. According to the principle of stable isotope fractionation, the carbon isotopic values of $CH_4$ from 3 spring groups in the Changbaishan Mountain region indicate that the magmatic gases from the 3 hot spring groups were released in different modes.

The carbon isotopic values of the Jinjiang hot spring group are about -25.6‰, which are close to the carbon isotopic values of $CH_4$ in most geothermal areas throughout the world. Magma gases come directly from magma chambers in the crust, and migrate and release from the top of the magma chambers upwards to the ground surface along the deep faults.

The carbon isotopic values of gases from the Julong Spring group are -36‰, lower than those of gases from the Jinjiang. Spring group. The initial source region of gases is also located in the crust, but the magmatic gases possibly first migrated into the geothermal reservoir at shallow levels and were retained there for a long period of time before they released together with geothermal water along the shallow faults to the Earth's surface. The carbon isotopic values of CH4 in the Hubin Sping group are very low, only about -47.9‰ on average, much lower than those of gases from other spring groups. This kind of magmatic gas would possibly come from the upper mantle, and it is considered to be the product of volcanic activity(Shangguan Zhiguan *et al.*2006).

Gases released from volcanic region is the best carrier to reflect information in the deep earth and is highly related with the tectonic condition and construction of material from the deep earth. Gases released from the Tianchi volcanic area are mainly He, $H_2$, Ar, $O_2$, $N_2$, $CH_4$ and $CO_2$. Among them, $CO_2$ is most dominant. In some gas-releasing spots there were also detected $H_2S$ and $SO_2$, but their contents are very low(Gaoqingwu *et al.*2004).

On the basis of the amounts of released gases at different spring spots and the sensitivities of various gases to magmatic activity, the Changbaishan Volcano Observatory selected He, $H_2$, $O_2$, $N_2$, $CH_4$ and $CO_2$ to carry out regular monitoring and observation. During 1999–2006, the SQ-206 gas chromatograph was employed and since June 2001, the Sp-3420 gas chromatograph has been used for observation. And sampling was conducted generally at an interval of 3- 7 days.

$CO_2$ is the most important elements in the releasing gases under the Changbaishan volcanic retion. Its thickness can reach 90% or more and relatively stable. The $CO_2$ in the releasing gases from hot springs maybe includes two elements. One is from the free gases under the ground and another is from hot water deeper under the ground which forms by decreasing pressure. After 2006,the $CO_2$ in the two observed hot springs has been all decreased simultaneously ,this fact should be paid attention to as well.

He is inert and rare-gas which has light mass, can move fast and has intense penetrating ability. It is one of the most reliable gases to geological environment for its lightly disturbance in moving process. Thus, He is the most important micro content gas in latter-day volcano and active tectonic region. There are a little He in most releasing gases of Tianchi volcano.

$H_2$ is a reducibility gas and also a high temperature gas, it is often connected with temperature. $H_2$ in the releasing gases of Tianchi volcanic region is one of the microscale component. No. 9 hot spring is a high temperature spring, the temperature of it is 4 degrees higher No. 15 hot spring. The He and $H_2$ in No. 9 hot spring is relatively higher the in the No. 15 hot spring. Sometimes man can't detect these two gases in No. 15 hot spring.

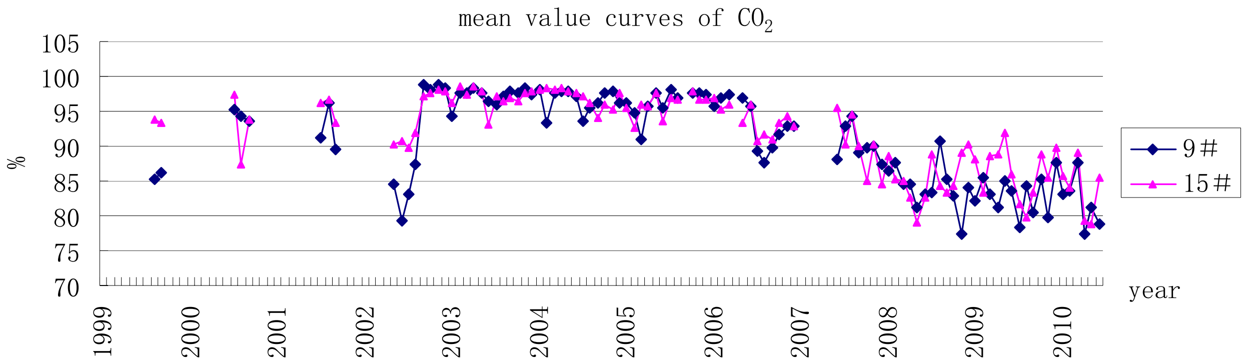
$CH_4$ is hydrocarbon gas and its source is mainly organic formation. The $CH_4$ in hot water activity in volcanic region is obviously not organic formed. The rocks around the volcanic region are all basalts or trachytes. So the exclusive source of $CH_4$ in the volcanic region is deep earth, not metamorphic formed, and it must has some connection with magma activity. The $CH_4$ has no relation with the temperature of the water from the results of some parameters.

In 2003 and 2004, both He and $H_2$ increased greatly. The He contents rose up to $600\times10^{-6}$, and the $H_2$ contents up to $2700\times10^{-6}$. During this period, volcano -seismic activities were frequent. On December 17, 2004, a ML 4.4 tectonic earthquake broke out and on April 15, 2005, a ML 4.0 one broke out. So the variation of gas contents can be regarded as an indicator of magma activity.

In October and November, 2006, He, $H_2$ and $CH_4$ rose up further. In the same period, a series of volcano-seismic activities occurred, including the ML 2.6 tectonic earthquake on Nov. 11, 2006. It has been again proved that the concentration ratio of volcanic gases has a close sensitive relation with magmatic and volcanic activities.

The temperature of No.9 and No. 15 hot springs uprised about 1 degree in 2003 and then kept on this level stably .This fact just corresponded with the seismic activity in the same time.

After May 2010, the temperature in the two hot springs uprised 2℃ simultaneously, and the observing environment had no change in the same time. Whether it is abnormality or not for The uprising of the temperature in the hot springs should be convinced in future, for there was no abnormality appeared in other observing items.


mean value curves of $CO_2$
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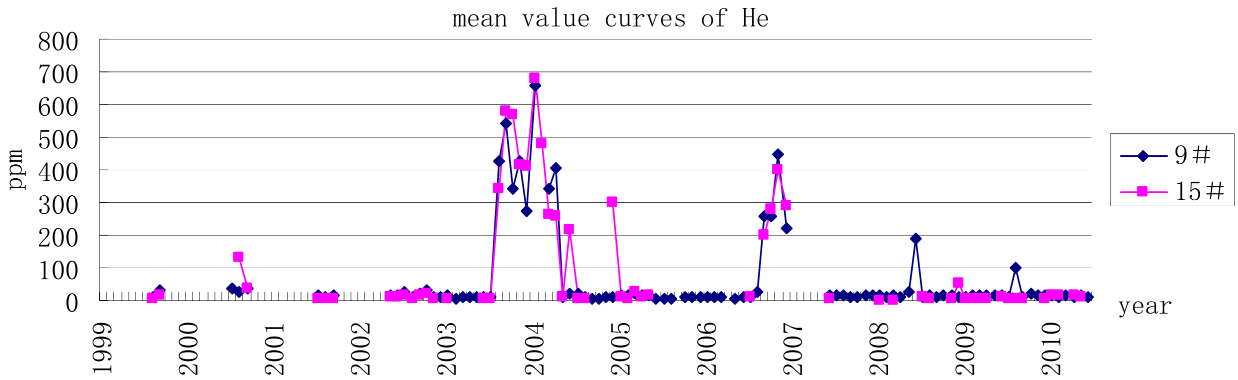
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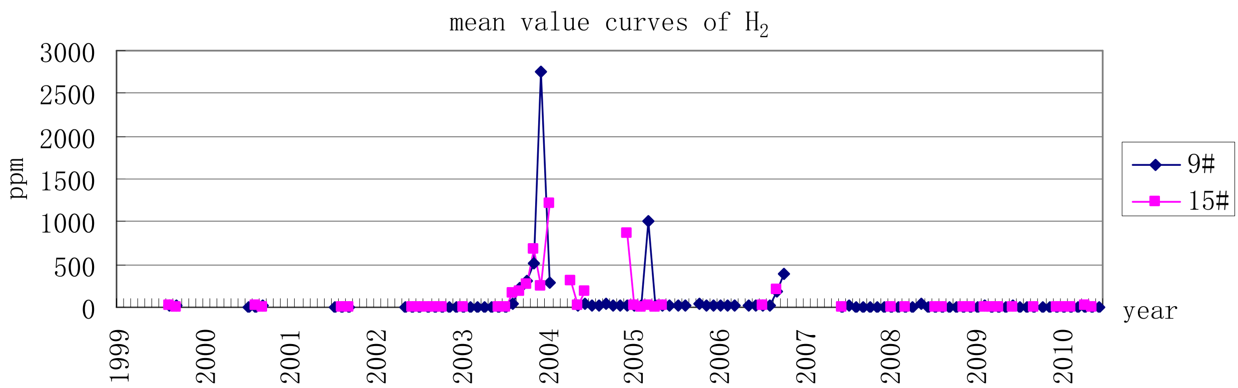
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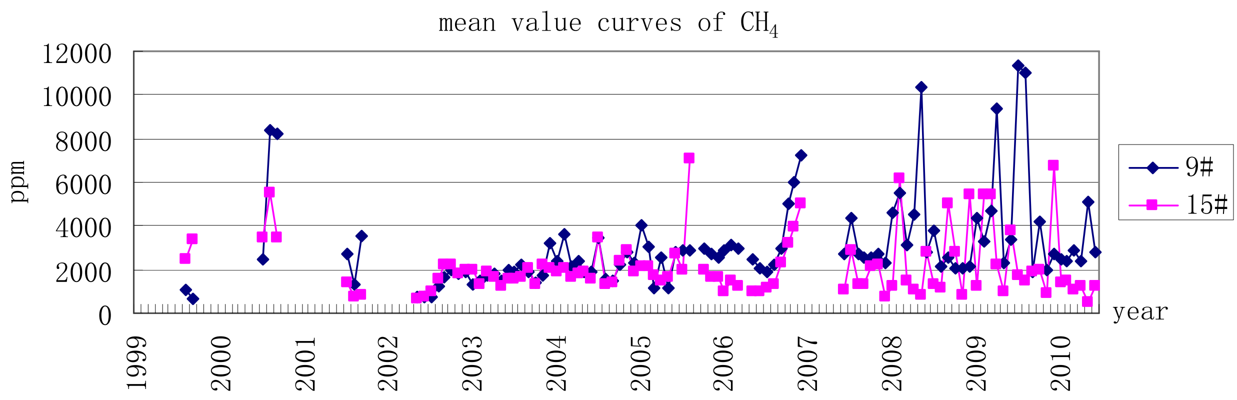


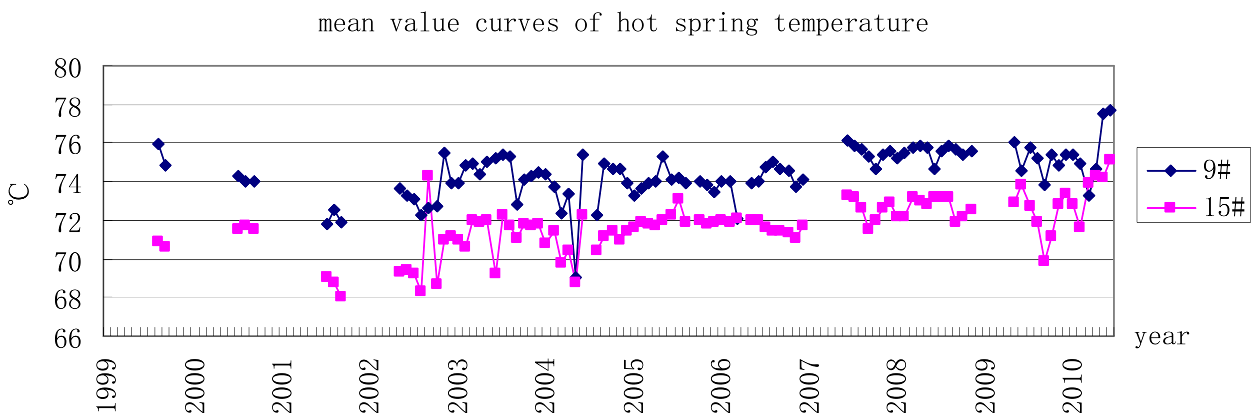


Fig 3.1 monthly average value of several mainly gas consistence variation and the water temperature

Fluid geochemistry is one of the most effective approaches to detect magmatic activities and predict eruptive hazards caused by active volcanoes. Volcanologists both at home and abroad have already conducted deep-going research on fluid chemical composition and magmatic activities, and got great achievements. In 2002–2005 there occurred magmatic disturbance and volcanic earthquakes, and abnormal phenomena were observed through isotope geochemical research and gas observation, which further proved that fluid geochemistry is so important in predicting the eruptive hazards caused by active volcanoes. The Changbaishan volcano is one which possesses most potential eruption risk. Because of the limited conditions, isotope geochemical observation can't be carried out on a continuous basis, but it can be dome regularly every year together with gas analysis to predict volcanic activities. If the volcano is too active, continuous isotope geochemical observation and the sampling density for routine components should be increased. $H_2S$ and $SO_2$ are the product of magmatic activity. Before and during volcanic activities, these two gases would rise up sharply. At present, in the Changbaishan volcano region, $H_2S$ and $SO_2$ are low. In this situation, if sulphur release is a little higher, the dynamic state of sulphur in gases will change obviously. So $H_2O$ and $SO_2$ are the sensitive and important gas components at the time of volcano eruption. Research work on $H_2S$ and $SO_2$ should be done regularly and continuously.

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# PROGRESSES ON PHYSICAL VOLCANOLOGY IN CHINA: AN OVERVIEW

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ABSTRACT: There were some significant progresses on the physical processes of volcanic activities in the Quaternary volcanic area in China in the past few years. The physical processes of solidification, fractional crystallization and stability of magma chamber, the dynamics in volcanic conduit and eruption column, and the transport and emplacement of pyroclasts and lava flow are given emphasis on and reviewed. The fractal features of pyroclasts and lava flows and the nonlinear processes existing in the dynamic system of the magma chamber are especially commented.

KEYWORDS: magma chamber, volcanic conduit, eruption column, volcanic products, physical processes, nonlinear processes

## I. INTRODUCTION

Physical volcanology is a multidisciplinary subject. Many principles of physics, especially thermodynamics, fluid mechanics, rheology and geophysics, were applied to volcanology and volcanic geology, mostly to the evolution of magma chamber, volcanic conduit dynamics, eruption column physics, pyroclastic flow transport mechanisms, etc.(Sparks et al., 1997; Gilbert et al.,1998; Freundt et al., 1998; Dobran 2001; Houghton et al., 2000; Parffit et al., 2008). The variables involving in the physical processes of volcanic activities, eg. temperature, pressure, viscosity, density, yield strength, etc. are fundamental and significant to acquire the differences and relationships among the various eruption types, and the numerical simulations of spatial-temporal characteristics of the volcanic products.

In the late 1980s to early 1990s, the conception and significance of physical processes of magmatic movement and volcanic eruption had been introduced by some researchers in China (Ma, 1986; Deng, 1989; Wei et al., 1991; Zhao, 1995). Since the late 1990s, the physical volcanology on the Holocene potentially eruptive volcanoes in the Chinese Quaternary volcanic area gradually developed (Liu, 1998; Wu, 1998; Guo et al., 1998; Yang et al., 1996). In the past few years, the physical processes of solidification, fractional crystallization and stability of magma chamber, the dynamics in volcanic conduit and eruption column, and the transport and emplacement of pyroclast and lava flow were placed emphasis on and obtained some new results and discussion.

## II. PHYSICAL PROCESSES IN MAGMA CHAMBER

The stability of magma chamber is controlled by the interior factors such as the behavior of activities and the cooling rate of the magma chamber as well as exterior factors like the extrusion and vibration of the wall rocks around the magma chamber. Under certain conditions, the activities of the wall rocks around the magma chamber can play a crucial role in the stability of magma chamber, especially in the area with frequent crustal movement. The stability of the magma chamber of Laoheishan volcano in Wudalianchi area, Northeast China had been analyzed by the coupling of Duffing equations of the magma chamber (Peng et al., 2005). The dynamical complexity of the activities of its magma chamber exhibits four types: dissipation (fixed point attractor), collapse, stabilization (limit cycle attractor) and chaos (strange attractor) (Fig.1). Furthermore, by the principle of synchronization in the nonlinear science, Peng et al.(2007) found that the phases of oscillators were locked strictly when the evolution of properties of magma chamber approaches the critical state of respective attractor. This result may be useful for forecasting the volcanic activities with seismic data.

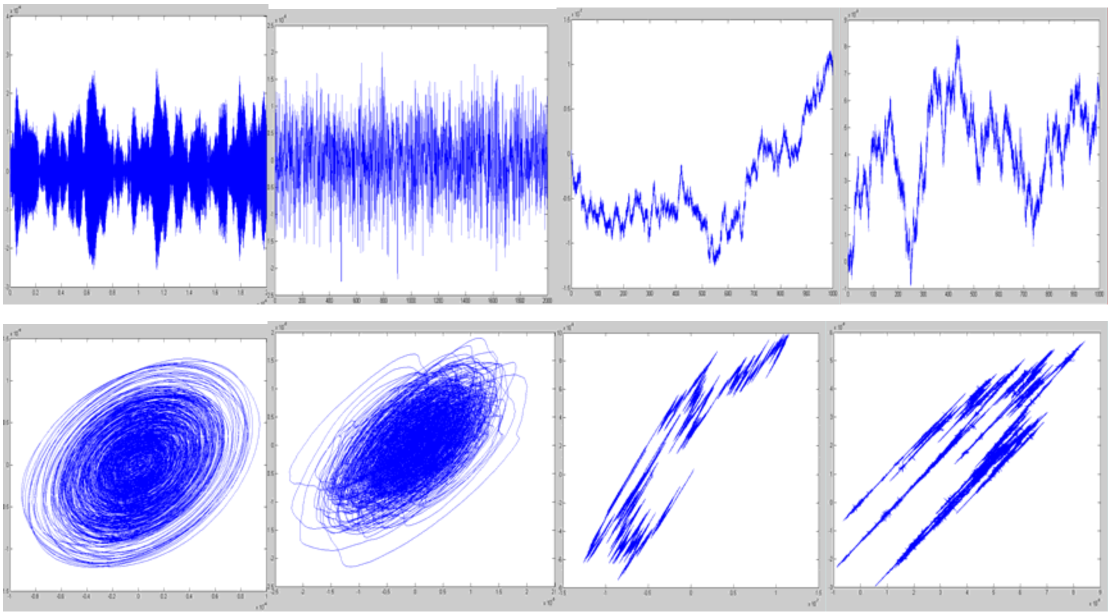

Fig. 1 Four types of vibration of the magma chamber (Peng et al.,2005)

On the basis of the heat conduction equation of the magma chamber, Peng et al. (2005) suggested that whether the Laoheishan magma chamber had been cooled or not, was closely related to the heating history of the rocks around the magma chamber, and that the magma in the magma chamber of Laoheishan volcano erupting in 1720-1721 had approached complete solidification.

Melt structure plays an important role in governing physical and thermodynamic characteristics of magmas. Wang (2004) calculated the NBO/T values (non-bridge oxygen numbers per unit of cations) on the concentrations of major elements and volatiles of Jingpohu Holocene volcanic rocks. The results showed that the proportion of lava in the total eruptive volume and its flowing capacity increased with NBO/T values rising. The lava with high NBO/T values was liable to generate the lava channel. Volatiles such as $H_2O$ and F were likely to concentrate in magma with high NBO/T values.

Recently, the magma up-moving processes within the magma prism beneath the Tianchi volcano, Changbaishan area, had been developed further by Wei (2010). The essence of the work was described in Fig. 2 which illustrated the relationship between the chamber pressure, dyke pressure and hoop stress. Before the Millennium Eruption, a maximum over-pressure in the comenditic chamber reached to $\Delta p_{max}$ = 6.25 MPa. From the layered chamber with radius of 3.5 km, the erupted magma occupied a space of 30 $km^3$ with the thickness of 700 m. The trachytic chamber got an over-pressure once as high as $\Delta p_{max}$ =15 MPa. The viscosity of critical erupting melt before the the Millennium Eruption was over

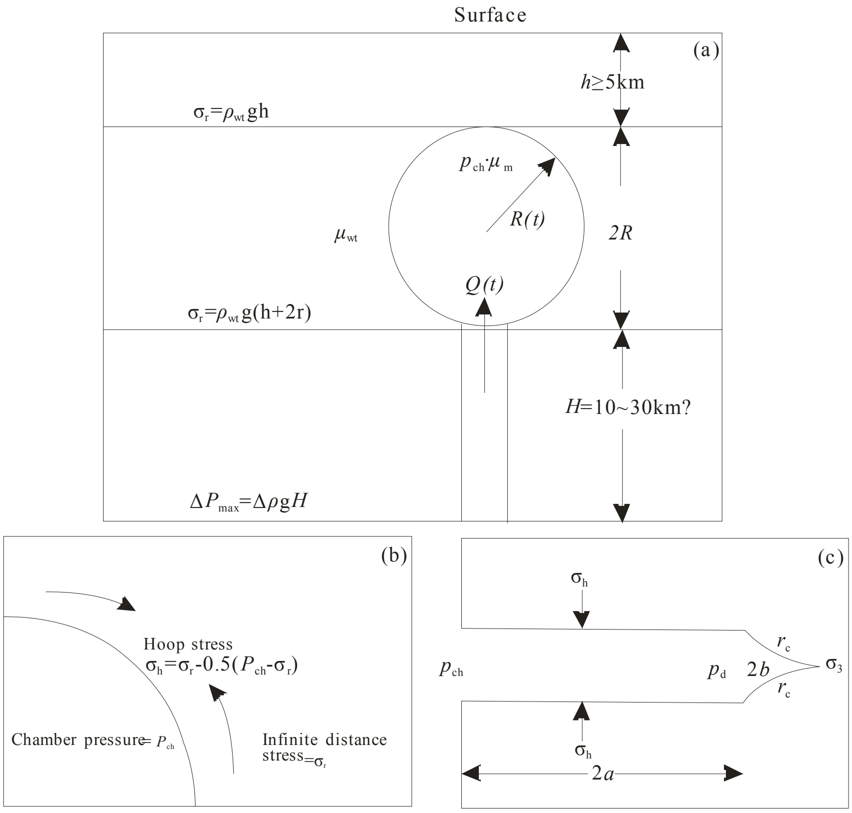


Fig. 2 Relationship between the chamber pressure, dyke pressure and hoop stress (Wei, 2010)

2.7×1010Pa • s-1. The viscosity of critical melt before the Qixiangzhan parasitic eruption was about 1.2×1011 Pa • s-1, which is consistent with high contents of crystals and bubbles in the magma. An average interval between the giant eruptions such as the Millennium Eruption was about thousands of years, which was much longer than the intervals of less explosive parasitic eruptions of hundreds of years. Once a zone of residual partial melt developed in the deep crust and started to prevent the basalt from eruption, the system became much more heating efficiently and the production of residual melt was accelerated. Large amounts of evolved residual comenditic melt could be produced in the Holocene, and then became unstable and intruded into the upper crust to form magma chambers large enough to result in the caldera-forming explosive eruptions.

## III. DYNAMICS IN VOLCANIC CONDUIT AND ERUPTION COLUMN

Magma uprising velocity is related to the viscosity, density and pressure of the magma, in the lower part of conduit. Wei et al. (2006) applied a usual model of a viscous liquid to simulate the flow dynamics of magma. In the intermediate zone, equations of mass conservation for liquid and gas phases transformation and equation of momentum for the mixture as a whole can be used while Darsy law is used for the gas phase nucleation and growing processes. Equations of mass conservations for the gas, accounting for free gas and gas in large particles, and equations of momentum for components of the mixture are used for the upper fragmented part of the conduit. There is 3% bubble volume in the chamber when the Millennium eruption maintained a plinian column from a 62 m diameter conduit. The magma becomes fragments when the bubble volume reached to 65% and expelled out of the vent in $145ms^{-1}$, a gas velocity of 170 $ms^{-1}$ and a gas-particle dispersion exit pressure of 12.2 MPa. Bubble volume in the magma chamber increased as high as 30%-40% before the caldera collapsed, which led to 70%-75% fragmented bubble volume, $180ms^{-1}$ gas exit velocity and 7-8 MPa exit pressure.

Qixiangzhan parasitic eruption is represented by weak explosive activity, from a 40m diameter conduit, with gas velocity 15-25$ms^{-1}$ and extrusive eruption. Porosity of the pumices in this case is lower than for Millennium eruption, 48% to 61% and pumice density is higher, 1.01-1.35 g $cm^{-3}$. During extrusive phase peak discharge rate could reach up to 42$m^3s^{-1}$(DRE) and porosity varies in the range of 70%-80%(Fig. 3).

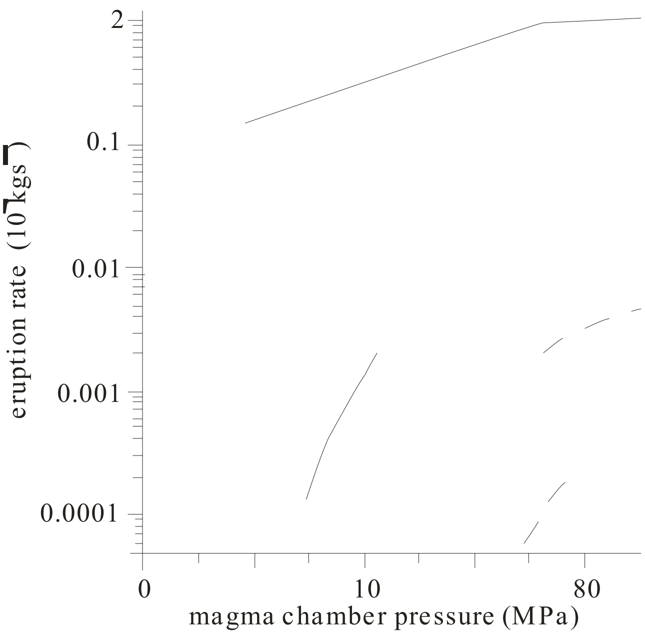


Fig. 3 Relationship between the magma chamber pressure and eruption rate of the Tianchi volcano (Wei et al., 2006)

As an essential and important type of volcanic activity on earth, phreatomagmatic eruption is characterized by groundwater-related explosive eruption and subsequent base surge deposit and maar lakes. Base surge deposit and maar lakes are widely distributed in the northeast China and the southern China. According to the maar lakes and base surge deposits of the phreatomagmatic eruptions in the Beibuwan district, southern China, Sun et al.(2005) studied the geological features of the base surge deposits and the dynamics of phreatomagmatic eruption and brought forward the transportation and sedimentation models. Also, for the volcanic plume, Mu et al.(2006) gave some discussion to its physical mechanism on the jet theory.

On the active volcanoes, Hong (2007) divided the physical situations of volcanic activities, from magma supply to eruption, into three phases (or stages), (1) the magma supply which the overpressure of magma chamber was the dominant parameter for whether the volcano was in the stage of dormancy or disturbance and the magma supply rate was essential, (2) the formation of conduit which the wall rock failed and a crack would be initiated when the overpressure exceeded the tensile strength of the wall rock and then the hydrothermal effects played an important role, and (3)the instability and eruption which magma moved in conduit, it interacted with overlying crust and the dynamics of magma flow in dykes was essential. The volcanic threat in China could be rated into seven levels as safety, attention, stand-by, alarm, threat, hazard and disaster.

IV. TRANSPORT AND EMPLACEMENT OF VOLCANIC PRODUCTS

*1. Fallout Deposits: Dynamics and Simulation*

Explosive eruptions generate convective columns and plumes which transport large amounts of particles and gas to tropospheric and stratospheric levels. Once particles leave the transport system they fall back to the ground under the action of gravity, following different paths depending on their size and density (Freundt et al., 1998).

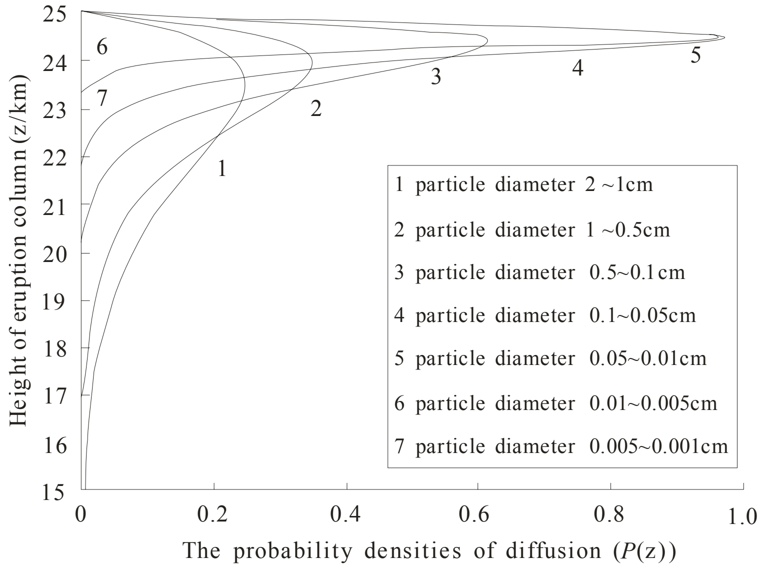


Fig. 4 The probability density of diffusion for different dimension of particles (Yu et al., 2007)

Zhao et al.(2002) adopted the mathematical model for the dispersion of tephra proposed by Suzuki (1983). On the basis of Suzuki´s formula, they compiled a practical program for simulating the dispersion of tephra fallout from a single volcano at one event of eruption. Zhang et al.(2003) improved Suzuki 2-D diffusion model and applied to simulate the distribution of volcanic eruptive sediment. A multi-peak structure and sediment distribution of the second peak were discovered. The effects of the wind speed and the dispersal parameter were discussed. The distribution of pyroclasts of Tianchi volcano in Changbaishan area was simulated. Recent simulation results summarized by Yu et al.(2007) indicate that most of tephra congregating at the top of the volcanic eruption column, and the differences of settling rates and densities of diffusion for different diameter particles (Fig.4).

The dynamic processes of volcanic bombs and blocks have been discussed recently by Liu et al (unpublished) . Three stages in the dynamics of bombs and blocks have been recognized, i.e. formation in the vent, ballistic flying from vent to landing surface and deformation during impingement on the surface. For each stages, they analyzed the main control factors, abstracted the basic movements and genetic models, and set up new functional relations of the main control factors and processes. The relations between the initial ejection velocity distributions and the initial ejection angles of bombs from volcanic explosions, show that the optimum angles resulting in maximum lateral distance is $55° < \theta < 75°$and 65° can be applied to ordinary situations except the processes requiring extreme precision.

*2. Emplacement Mechanism of Lava flows*

Wei et al.(2005) presented that lava flows in the Holocene volcanic territories in the northern Hainan Island, China, moved over a distance up to 8 km from their sources with a flow velocity about 1-10 m/s. The total duration of their eruptions might last for months or years, but some lava flows with 8 meter thickness might reach its distal location in one day. Volcanic hazards due to lava flows erupted from the four volcanic systems in the future may be destructive to farmlands and roads and cause fire disaster. Jin et al.(2006) calculated the flow velocity of Tianchi basaltic lava flow and the time duration of lava reaching its distal localities. The calculated velocity of the lava flow with 0.5 meter thickness and 5 vol% crystal contents was less than 1 m/s, while it reached up to 10m/s when the flow thickness increased to 2 meters. But if the crystal content in a lava flow with 0.5 meter thickness increases to 30 vol%, the lava flow velocity would decrease sharply to less than 0.12 m/s. The lava flow with 2 meter thickness lying to the northeast Tianchi volcano could reach its distal part in less than a day, but it needs ten days if the flow thickness would be 0.5 meter. The lava flow of Tianchi volcano might have a distance up to 50 km in the future eruption.

Li (2009) calculated the fractal dimensions of boundaries of Laoheishan pahoehoe lava flows and a'a lava flows, and the fractal dimensions of vesicles in the profiles of lava flows. The results showed that the boundaries of lava flows and the vesicles were statistically fractal. The fractal properties of boundaries of lava flows suggests that nonlinear processes are operating during the emplacements of lava flows because linear equations cannot produce fractals.

### *3. Particle Transport Mechanisms: Complexities during Eruption*

The particle size, separation, surface texture, and internal structure of pyroclasts produced by explosive volcanic eruption bear a close relation to the mechanism of volcanic eruption, the reaction degree between the magma and water, and the emplacement processes.

The field investigation showed that the volcanism in Longgang, Jilin Province had three types of eruptions, i.e. phreatic eruption, phreatomagmatic eruption and magmatic eruption. The materials from each kind of eruption showed different pyroclast feature, grain size and shape. By the fractal theory, Zhang et al. (2005) analyzed the fractal features of the grain size of pyroclasts from the Longgang volcanoes. Their results showed that the fractal dimension of the pyroclasts of phreatomagmatic eruption was smaller than that of the phreatic eruption, but greater than that of the magmatic eruption (Fig. 5). The values of fractal dimension could be used as parameters to distinguish the different types of volcanic eruption. For the Longgang volcanoes, the fractal dimensions of pyroclasts at Jinglongdingzi on the upper profile over the aquitard was greater than 2, and those at Xiaojinglongdingzi on the lower profile was less than 2. Fractal dimension values could be regarded as an indicator to differentiate various eruptive sources and classify stratum sequences associated with volcanoes. Their research demonstrated that the pyroclasts with fractal dimension less than two contained the anisometric grains of various content, and their values of fractal dimension were negatively correlated with the grain content.

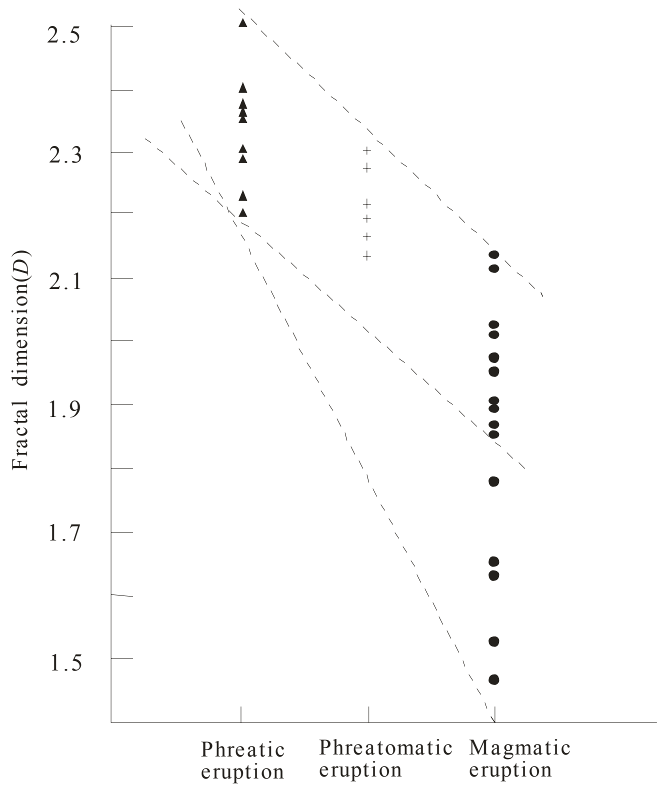


Fig.5 The fractal dimension of pyroclasts from different eruptive type (Zhang et al., 2005)

On the sampling from the field investigation in Tianchi Volcano, with the help of optical microscope and the scanning electron microscope (SEM), Miao (2008) studied the morphology and the sizes of vesicles in the white pumices, as well as yellow and black ones. The number densities of vesicles in the white pumices with average diameter 86 μm were much larger than the ones in the black pumices and the yellow pumices. Also, Yu et al. (2008) investigated some profiles in Longgang volcanic area, Jilin Province and identified the pyroclasts from phreatic, phreatomagmatic and magmatic explosive eruption had different compositions and morphology. Particle size analysis indicated that the feature of particle size distribution bears a good relation to eruptive type and the different eruptive type had different fractal dimension scope.

## V. PROSPECTION

In this review, the researches of various volcanic progresses from the perspective of physical volcanology had been drawn attention to and the physical principles could be applied to the different kinds of volcanic processes with different the scale, from small to large. Most of recent advances in the physical treatment are based on the field observation and theoretical calculation and appear to be well suited to describe the gross behavior of volcanic activities. In order to promote the development of physical volcanology, future researches should be aimed at characterizing the involving processes and phenomena in greater detail and improve the models to the state that the more accurate predictions of volcanic activities can be made. The researches will increasingly involve the experimental and numerical modeling, and make some efforts to explore the complexities and nonlinear dynamical behaviors involved in the volcanic system.

ACKNOWLEDGEMENTS

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# A REVIEW OF VOLCANO MONITORING PROGRAM IN CHINA

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ABSTRACT： The National Volcano Monitoring Network (NVMN) was established in 2006, which is composed with four provincial volcano centers under which six active volcanoes are monitored. These active volcanoes include Changbaishan Tianchi volcano and Longgang volcano in Jilin province, Wudalianchi volcano and Jingbohu volcano in Heilongjiang province, Tengchong volcano in Yunnan province, and Qiongbei volcano in Hainan province. As the headcounter of the active volcano monitoring and research of China, the major tasks of the National Volcano Monitoring Network Center are: data management and analyzing for all six volcano observatories; annual situation report on volcano activity to the administration; and volcano knowledge education and outreach to the public.

KEYWORDS: Active Volcano, Monitoring, NVMNC

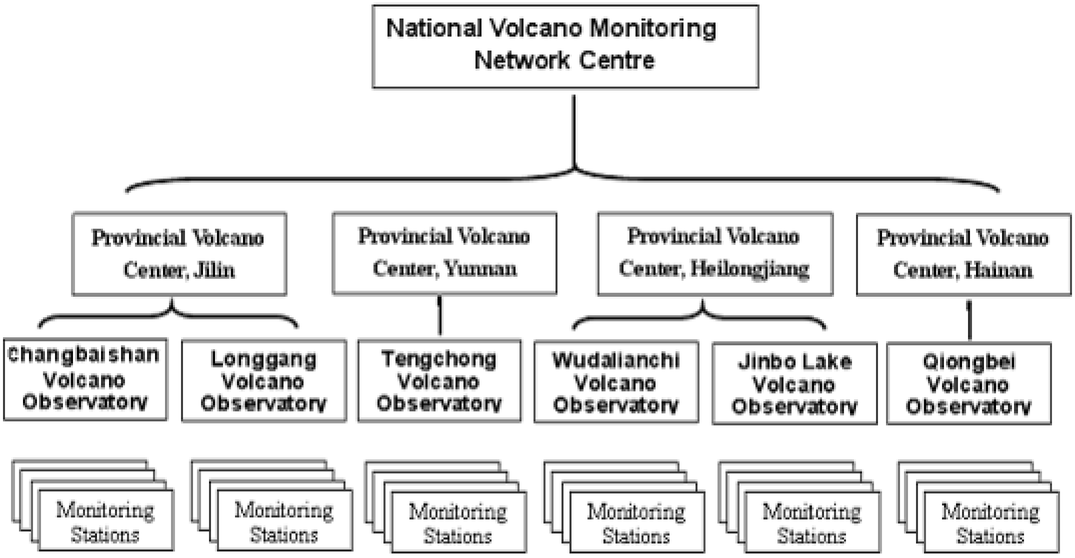
## I. INTRODUCTION

There was no much work done dealing with active volcanoes before 1990's in China because no many scientists believed that there are any volcanoes with eruption potential which could bring up large hazard in that period. In 1993, with administrative and financial support from the central government, Active Volcano Research Center of China Earthquake Administration (AVRCC) was established, which marked beginning of comprehensive studies of potential active volcanoes of China. Since then, a great deal of progress has been made in terms of both volcano monitoring and research in China. With the efforts from the scientists in the field of volcanic geology, geophysics and geochemistry for over 20 years, we found that there are at least 14 volcanoes with eruption potential in China. The National Volcano Monitoring Network consists of 6 volcano observatories which include Changbaishan Tianchi volcano, Longgang volcano, Wudalianchi volcano, Jingbohu volcano, Tengchong volcano, and Qiongbei volcano. The major monitoring methods that have been applied so far are seismology, ground deformation and gas geochemistry.

## II. THE NATIONAL VOLCANO MONOTORING NETWORK (NVMN)

The NVMN of China is set up with a pyramid structure which has four classes from the bottom to the top, i.e. monitoring station, observatory, provincial center, and national center (fig. 1).

Fig.1 Frame structure of the National Volcano Monitoring Network Center




*1. Monitoring Station*

As the basic element of the network, a monitoring station is build up for data collection, storage, and transferring. According to different monitoring purposes, such stations can be classified into seismic station, ground deformation station, geochemistry station, and gravimetry station.

*(1) Seismic station*

It is applied to monitor earthquake activity in volcano region. Seismometers of both short period and broad-band frequency are installed.

*(2) Ground deformation station*

Both GPS measurement and precision leveling are applied to monitor the possible expansion of mountain.

*(3) Geochemistry station*

In a geochemistry station, gas samples are collected from hot springs and gas emission spots for the purpose of chemical composition analysis.

*(4) Gravimetry station*

Both permanent and mobile gravitation measurements are applied to monitor the gravitational variation at the surface.

*2. Volcano Observatory*

A volcano observatory is in charge of data processing, data storage and management, maintenance of monitoring station, and fast report of volcanic earthquake events.

*3. Provincial Volcano Center*

A provincial volcano center is composed with one or more volcano observatories. The function of a provincial center includes data collection from volcano observatories, data storage and management, fast report of abnormal precursor of volcano eruption.

*4. National Volcano Monitoring Network Center*

As the headcounter of the active volcano monitoring and research of China, the major tasks of the NVMNC are: data management and analyzing for all six volcano observatories; annual situation report on volcano activity to the administration; and volcano knowledge education and outreach to the public.

## III. CURRENT SITUATION OF VOLCANO MONITORING IN CHINA – A CASE OF CVO

Table 2 Volcano Observatories and Main Methods used in the Volcano Monitoring of China

| **Volcano Observatory** | **Seismic Station** | **GPS Site** | **Precision Level Lines (sites)** | **Gravity** | **Gas Geochemistry (sampling sites)** | **Tilting** |
|---|---|---|---|---|---|---|
| Changbaishan | 11 | 16 | 2(28) | 1 | 1(5) | 2 |
| Tengchong | 8 | 20 | 4(97) | | 1(200) | |
| Wudalianchi | 5 | | | | 1 | |
| Jinbo Lake | 5 | 8 | | | | |
| Longgang | 4 | | | | | |
| Qongbei | 4 | 7 | | | 1 | 1 |
| Total | 37 | 51 | 6(125) | 1 | 4(205) | 3 |

Currently, six volcanoes are under comprehensive monitoring by six observatories respectively, in which Changbaishan volcano observatory (CVO) is in the biggest scale and the longest monitoring history (Table 2). CVO was established in 1996, but the monitoring work started in 1999. CVO became the National Key Observatory of the Science and Technology Administration of China in 2001. a comprehensive monitoring of magmatic activity of Tianchi volcano has been carried out in order to understand the magmatic processes and potential risk of explosive eruption in future. Based on the 10-year period (1999-2009) monitoring by means of seismology, ground surface deformation, volcanic gas geochemistry, and satellite thermal infrared remote sensing, we observed the ascent process of magma at Tianchi volcano during 2002-2005 (Wu et al., 2007; Cui et al., 2007; Shangguan and Wu, 2008; Ji and Xu et al., 2010). Our observation is strongly supported by the following evidences. 1) Increase of number of earthquakes per month from less than 10 events before 2002 and after 2005 to greater than 70 events in period of 2002-2005, which suggests about 10 times increase in seismic intensity; 2)Distinctive horizontal expansion near the crater of Tianchi volcano from GPS observation, and 46mm upward displacement near the crater from leveling survey between 2002 and 2003; 3)Increase of $^{3}He/^{4}He$ ratio in gas from hot springs near Tianchi volcano; and 4) Intensive thermal anomaly during 2002 -2005 from satellite thermal infrared remote sensing analysis. These monitoring evidences mentioned above suggest a magma inflation and upwelling activity in the magma chamber. Such magmatic activity may be attributed to the intensive subduction of the Northwest Pacific plate toward the Eurasian plate.

## IV. RECENT DEVELEPMENT IN APPLICATION OF SATELITE REMOTE SENSING IN VOLCANO MONITORING

As a new technique for space to earth observation, the satellite thermal infrared remote sensing has been applied in the volcano monitoring over the world in recent years, which has been proved to be able to conduct an effective, macroscopic, periodical and long-range volcano monitoring work. Satellite thermal infrared remote sensing is a very important means for us to obtain land surface thermal information which contains the contribution of magmatic activity in the volcano area. In principle, the thermal radiation information recorded by satellite thermal infrared sensors is processed first to get rid of different interference noises by different correction methods, and then the brightness temperature difference between the volcanic geothermal anomaly areas and normal areas can be used to analyze the potential volcanic activity according to the temporal and spatial characteristics [Bo and Hua, 2003]. Generally, a long-term observation and monitoring of the volcanic geothermal system for a particular volcano area is useful to figuring out the spatial and temporal thermal variation and to finding out the abnormal temperature change, which may lead to the possible precursor of volcanic eruption. In recent years, much work has been done to study the possibility of using remote sensing technique as a tool for volcano monitoring [Bo et al, 2001; Qu et al.,2006 ]. Some typical results are presented by Ji et al's work in 2010. In their study, a total of 9 sets of thermal infrared data including 7 Landsat TM/ETM and 2 ASTER images from 1999 to 2008 are processed and analyzed, and the temperature anomalies caused by magmatic activity of Tianchi volcano are obtained. Their results indicate that there existed a possible magmatic upwelling event from 2002 and 2005, and then the upwelling phenomenon receded gradually to normal status. Above observation and conclusion are consistent with the results from different observation methods in the same area, e.g. seismic monitoring, ground deformation from GPS measurement, and volcanic gas geochemistry monitoring in some degrees. Therefore, it is implied that the satellite thermal infrared remote sensing technology is capable of detecting the magmatic activity underground.

## V. CONCLUSIONS

With the efforts from the Chinese scientists in the field of seismology, geophysics and geochemistry for over 20 years, a great deal of progress has been made in volcano monitoring of China. However, comparing to the USA, Italy and Japan, whose volcano monitoring work is at least 50 years earlier than that of China, we are behind in the period of monitoring data accumulation. Moreover, there is no modern volcano eruption event occurred in continental China in about recent 100 years, which makes it very difficult for us to determine the imminent precursor of a possible eruption. Therefore, the volcano monitoring of China has a long way to go.

## ACKNOWLEDGEMENT

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# NEW ADVANCES IN PETROLOGY, GEOCHEMISTRY AND GEOCHRONOLOGY OF CENOZOIC VOLCANIC ROCKS IN CHINA

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Volcanic rocks are a window to explore the interior of the Earth, because the geochronology, petrology and geochemistry of volcanic rocks can be utilized to trace and reveal the chemical compositions and evolution processes of the Earth. Recently, based on the previous works, a plenty of high-quality geochemical data have been being reported because of improved analyzed technology. In addition, recent petroleum drillings also provide a lot of new information on some buried areas and littoral areas (eg., Zhang et al., 2006; Zhang et al., 2009; Peng et al., 2006; Gu et al., 2006), which has played an important role on the further study of petrogenesis and geodynamic settings of the deep earth. In this paper, we summarize the main advances on the Cenozoic volcanic rocks of China in the past 5 years, and then present our own viewpoints for the future works on volcanic rocks in China.

## I. ADVANCES ON CENOZOIC VOLCANIC ROCKS

### *1. Spatial and Temporal Distributions of Volcanic Rocks*

Spatial and temporal distributions of Cenozoic volcanic rocks in China have been preliminarily identified by recent geological surveys and a large number of special studies. Cenozoic volcanic rocks are predominantly distributed in eastern China, Tibetan Plateau and its adjacent areas, and minor in Central Asian orogenic belt, Xinjiang, such as Halaqiaola in Altai mountains (Huang et al.,2006), Tuoyun Basin in Wuqia County (Liang et al., 2007) and Xikeer in Tarim Basin (Chen et al., 2008). Except for some marine volcanic rocks in Taiwan, south Chinese sea, and Tibet, most are terrestrial. Three episodes of the Cenozoic volcanic rocks have been recognized, i.e., Paleocene, Miocene-Pliocene and Quaternary. However, some sub-episodes can be divided in some areas.

In recent 5 years, one of a spectacular achievement is that zircon U-Pb dating technologies (such as SHRIMP and LA-ICP-MS) have been extensively applied in China and yielded a plenty of high-quality geochronology data. However, most of Cenozoic volcanic rocks are basalts, as we all know, and it is difficult to separate zircon grains from basalts. Thus, zircon U-Pb datings are rarely applied in Cenozoic volcanic rocks, and $^{40}Ar$-$^{39}Ar$ and K-Ar methods are much more commonly utilized to date instead (eg., Li et al., 2005, 2006; Gao et al., 2006; Zhai et al., 2009; Yang et al., 2006; Xie et al., 2008; Yu et al.,2009; Li et al., 2009; Shan et al., 2009). However, there are some exceptions. For instance, Liang et al. (2007) obtained a SHRIMP U-Pb zircon age of 48.1±1.6Ma of olivine basalt in the Tuoyun aera，Wuqia County，Xinjiang; a same method for the basalts from the Piqiang Basin in the southwest Tianshan yields an average age of 46Ma by Li et al. (2009). Although the ages are quite scattered, the youngest ages are very close to the previous $^{40}Ar$-$^{439}Ar$ datings. Interestingly, Luo et al. (2006) got the youngest SHRIMP U-Pb age of 3.82±0.08Ma of the alkali basalts from Kangxiwa, West Kunlun mountains. However, how these $SiO_2$-unsaturated basic magmas can crystallize zircon is not understood. In addition, U-Th disequilibrium system dating technology is also initially applied in

Holocene volcanic rocks (Zou et al.,2010).

Cenozoic volcanic rocks in eastern China have been well studied. The main fruitful achievement is to produce a number of new high-quality age data. For instance, Yang et al. (2006) proposed that there are multi-episodes of Cenozoic volcanism in the depression of the eastern Liaohe Basin in the light of K-Ar ages, and concluded that eruption began at 65Ma, and experienced 42-38Ma and 32-25Ma at peak activity, which are consistent with regional tectonic movement of eastern China: rift stage, extension stage and intense strike-slip stage. Based on K-Ar datings, Zhang and Han (2006) recognized that the main eruption episodes of the Jining basalts, Inner Mongolia are Late Oligocene to Miocene, which can be divided into three cycles: ca. 33Ma、22.8 to 22.1Ma and 12.2 to 9.4Ma. Thermoluminescence, OSL and $^{14}C$ datings are the most important methods applied for Holocene volcanic rocks. These methods have played critical roles on identifying the history of active volcanoes. Tianchi volcano in the Changbaishan, Jilin province, is one of the most dangerous volcanoes in the economic zone of eastern China. On the basis of field observations, Fan et al. (2005, 2006a, 2007) revealed the history of volcanic activity by different dating methods, i.e., trachybasalt shield formed (2Ma ago) in the early stage of Early Pleistocene, and then trachyte cone (~1Ma) in the late period of Early Pleistocene and finally pantelleric magma explosively erupted during Holocene. In addition, the new age data also shows that there are some young volcanoes in the areas surrounding northern Gulf of China, such as Leizhou Peninsula, Hainan Island and Weizhou Island. For example, based on thermoluminescence and OSL methods for the sandstone xenoliths from volcanic rocks and $^{14}C$ methods for the shells from phreatomagmatic base surge deposit, Fan et al. (2006b, c) concluded that the Leihuling and Maanling volcanoes in the north Hainan are Holocene at ca. 10ka, and the Weizhou Island is ca. 30ka. The rocks from Leihuling and Maanling volcanoes are olivine tholeiite and quartz tholeiite respectively, whereas alkaline olivine basalts and basanites in Weizhou Island occurred at early and late stages respectively.

Tibetan Plateau is a natural laboratory to study continental dynamics, and has been received much more attention from international geologists. Due to poor transportation conditions, some local geology is not well understood. The recent geological survey has provided a large number of first-hand geological information, which makes us more clearly understand the spatial and temporal distributions of the Cenozoic volcanic rocks. The previous studies (e.g., Chung et al., 2005) have shown that Cenozoic volcanic rocks in Tibetan Plateau exhibit the regular spatial and temporal distribution as follows: In the Gangdise (Lhasa block) region, the Linzizong volcanic rocks are extensively exposed, and they are chiefly composed of medium potassium-high potassium calc-alkaline series, including basalt-( trachy)andesite-trachyte-dacite-rhyolite, whilst potassic volcanic rocks, including leucite phonolite-trachyte, and they were dated at 65-40Ma (Xia et al., 2009). The Linzizong syn-collision volcanic activity in the south of Gangdise occurred at ca. 65Ma ago, which record the beginning of India-Asian collision. The Qiangtang volcanic area can be further divided into West, South and North Qiangtang. The West Qiangtang is predominated by mafic volcanic rocks that consist of trachybasalt-(trachy) andesite, which belongs to medium potassium-high potassium calc-alkaline series and shoshonite series. They have been dated at ca. 60-46Ma, which is the earliest volcanism in northern Tibet; Rock types in South Qiangtang are quite complicated. The volcanic rocks in the Yulinshan consist chiefly of leucite porphyry, phonolite, aegirine trachyte, aegirine-nephelite trachyte, nosean trachyte with minor other rocks. The Nadingcuo volcanic rocks are composed of andesite, basalt, latite, rhyolite, dacite and pyroclastics. The Lagala volcanic rocks are mainly olivine-phyric basalt. The Zougouyouchagou volcanic rocks are high-K calc-alkaline andesite and dacite (Li et al., 2006); The rocks in North Qiangtang include basanite, tephrite, echodolite, andesite, trachyte, dacite, rhyolite, which belongs to high-K calc-alkaline series and shoshonite series. The volcanism in the North Qiangtang display west progression, and at least can be divided into three stages: the middle-late Eocene (40-35Ma), Late Oligocene (ca. 25Ma), and the middle-late Miocene (ca. 10Ma). The interval of peak volcanism is ca. 10 Ma, and the peak volcanism tends to be weaker at late stage. The West Kunlun volcanic rock assemblage contains basaltic trachyandesite- trachyandesite-trachyte-rhyolite, and some with tephrite-phonolite, which belongs to high-K calc-alkaline series and shoshonite series (Zhang et al., 2008). They mainly formed during Neogene. The volcanic rock assemblage in Hoh Xil is trachyandesite-trchayte-rhyolite, whereas phonolitic tephrite ocurred in the Whale Lake region, which are of shoshonite series. The volcanic rocks in the middle part is younger, whereas those in the east and west parts are older. As a whole, the Cenozoic volcanic rocks strike in west-east, and distribute along the suture zone. Cenozoic volcanism in Tibet has the trends of north and west progression.

2. *Petrogenesis of Volcanic Rocks and Geodynamic Processes of Deep Earth*

In recent years, not only has isotope chronologic technique been greatly improved, but the precision of the trace element analyses as well. Microprobe analysis techniques and other isotope analysis techniques (such as Re-Os isotope system, noble gas isotope system and U-Th non-equilibrium system) are also widely applied for petrogenesis of volcanic rocks. These new methods provide a valuable tool to help us understand the petrogenesis. Although the Cenozoic volcanic rocks in eastern China are well studied, the recent studies are still fruitful. The Tianchi volcano is one of the youngest volcanoes in China, and the petrogenesis and eruption mechanism has been current issues. On the basis of detailed field observations and petrographic studies, Fan et al. (2006a, 2007) and Chen et al.(2008b) suggest that fractional crystallization is a critical factor to produce different magmas. Furthermore, they found some petrographic evidences of magma mixing. Thus, Fan et al. (2006a, 2007) and Chen et al. (2008b) proposed that the periodic replenish of magmas, fractional crystallization and magma mixing are the main reasons to produce bimodal volcanic rocks, and also the key mechanism triggering Tianchi volcano, and that the subduction of western Pacific plate and the back arc spreading of Northeast Asia continent is the geodynamic settings of the Changbaishan volcanic activity. In addition, Zou et al. (2008) estimated that the magma evolution time from low $SiO_2$ (47.5%) basalt to higher $SiO_2$ (50.4%) basalt is within 10 thousand years (10ka). The magma evolution time from trachyte to rhyolite at Tianchi volcano is also less than 10ka. Other researchers also believe that the tectonic settings of the Cenozoic volcanic rocks near the Changbaishan are related to the Pacific plate subduction (eg., Wang et al.,2006; Chen et al.,2008b; Zhang et al.,2006; Sui et al.,2007). In contrast, a few workers believe that the Cenozoic volcanic rocks in eastern China such as Hainan Island may be related to mantle plume (eg., Zou and Fan, 2010), but most people agree that the formation of Cenozoic volcanic rocks in eastern China can not be ascribed to the subduction of Pacific plate, but they formed in a rift setting, resultant from lithosphere-asthenosphere interaction following upwelling asthenosphere (Xu and Xie, 2005; Xu et al., 2005; Tang et al., 2006; Peng et al.,2006; Yan and Zhao, 2008; Du et al., 2008; Qin et al.，2008; Zhang et al., 2009; Fu et al., 2009; Dong et al., 2010). This viewpoint is argued against mantle plume model which is not supported by the recent geophysical data and relatively low $^3He/^4He$ (5-7Ra, Chen et al., 2007). Most investigators agree that although crustal contamination has somewhat affected the compositions of the Cenozoic basalts, it is not a key factor, compared with the mantle sources. Furthermore, heterogeneous mantle sources are believed to be caused by asthenosphere-lithosphere interaction. In general, alkali basalts are thought to be produced by low degree of partial melting of deep asthenospheric mantle, whereas tholeiites are resulted from high degree melting of shallow lithospheric mantle or with contribution of minor asthenospheric mantle materials (Xu et al., 2005; Chen et al., 2007). It is also believed that the mantle for the source of alkaline rocks had been metasomatized prior to melting (Shao et al., 2008). However, the petrogenesis of peralkalic magmas remains controversial. For the petrogenesis of Pleistocene nephelinolite in the Wudi area, Shandong Province, Luo et al. (2009) suggested that it is mainly related to the mantle peridotite sources contain some pyroxenolite or amphibolite, whereas Zeng et al. (2010) argued that carbonatite in mantle peridotite of source is a root cause of peralkaline nephelinolite should be originated from carbonated peridotite. In summary, although there are some different viewpoints on the genesis and tectonic settings of Cenozoic volcanic rocks in eastern China, the overall general interpretation is unanimous.

In contrast, the Cenozoic volcanic rocks in western China is relatively poorly studied, compared with east China, but new data, including high-quality geochronologic and geochemical data have been rapidly increasingly reported in recent years. These data provide some important constraints on petrogenesis.

Since the 70s of last century, there have been many new progresses on structural tectonics, properties of deformation and the uplift mechanism of Tibetan Plateau, and different continental dynamics models have been proposed. However, many important scientific issues on origin and evolution of Tibetan, such as the time of continent-continent collision, detailed processes and mechanism of the collision, the cause of NS-trending rift system, the time and mechanism of crustal thickening etc., are still debated. The recent studies on the Cenozoic volcanic rocks provide an important constraint on these issues. For instance, Hou et al. (2006) and Hou and Wang (2008) proposed a three stage model of collision orogen (convergence in main collisional convergence, late collisional tectonic transform and post-collision extension), which helps understand the processes and mechanism of continent collisional orogenic belt. Their main viewpoint is summarized as follows: (1) main collisional convergence stage: the main collisional convergence caused by India-Asian continent began at 65Ma, and lasted to 41Ma, leading to thickening crust. The main collisional magmatism mainly occurred in the southern margin of the Asian continent, ~5000m thick Lingzizong volcanic rocks (64-43Ma) are extensively exposed in Gangdise, indicating the following processes: continental slab subduction (65-52Ma) →slab break off (52-42Ma) →low angle (＜40Ma) slab subduction; (2) late collisional tectonic transform stage: it is characterized by continuous convergence between India and Asian continents and north-south compression, and relatively horizontal movement among blocks along large shear zones. Intracontinental subduction in late collisional stage could induce the lateral flow of subcontinental mantle and upwelling of deep asthenosphere, and created potassium-ultrapotassic magmatic belt. The peak magmatism is $35 \pm 5$ Ma. (3) post-collisional extension stage: The post-collisional magmas formed under north-south compression regime. At the early stage (＞18Ma), lower crustal flow and upper custal shortening are the main processes. Lower crust plastic flowed and extruded southward; At the late stage (＜18Ma), crustal extension and rifting are the main processes: EW Extension perpendicular to collision zone produced a series of NS normal fault system (14-10Ma) across the Tibetan Plateau, rift systems and rift basin. The post-collisional magmatism is characterized by rock assemblage which formed under extension setting in response for breakoff of subduction plate and thinning of lithosphere, producing mainly potassium and ultra-potassic volcanic rocks and K-rich adakitic rocks (Wang et al., 2008). Some new interpretations on the petrogenesis of volcanic rocks, e.g., the distribution of potassium and sodium volcanic rocks, have been yielded. The Cenzoic potassic volcanic rocks in Tibetan Plateau were commonly considered to be derived from an ancient enriched lithospheric mantle. Ding et al. (2007) suggest that potassium-ultrapotassic volcanic rocks in the northern Qiangtang were derived from a relatively primitive mantle source, and thereafter contaminated by metasedimentary lower crust-derived partial melts. Although those from the southern Qiangtang are also derived from a primitive mantle source, the sources are more primitive than those from the nothern Qiangtang (no contribution of metasedimentary crust-derived melts). These authors propose that whether there is the contribution of crustal materials is a key factor to produce potassium or sodium volcanic rocks. On the basis of granulite xenoliths in volcanic rocks, Lai and Qin (2008) believed that potassic magmas may be related to some special substances (not typical gabbroic materials) in lower crust. A variety of models, e.g., crustal contamination, partial melting of incompatible element-enriched mantle, partial melting of phlogolite-bearing mantle peridotite, have been proposed to interpret the petrogenesis of ultra-potassic volcanic rocks that are a characteristic rock in Tibetan Plateau. In recent, Zhao et al. (2009) proposed a new interpretation that the formation of ultrapotassic rocks could be attributed to additions of enriched components in the source that underwent a two-stage metasomatic enrichment event, and the enriched component may be derived from the ancient basement of Gangdise or the subducted Indian continental lithosphere. Zircon grains from the ultrapotassic rocks in Gangdise recorded at least two enrichment events, and two kinds of components could have been involved. One is the recycled ancient crustal basement beneath Gangdise prior to the subduction of Indian continental lithosphere; the other one is the contribution of subducted Indian continental lithosphere to enriched lithospheric mantle. Zhang et al. (2008) suggested that the K-enriched degrees of ultrapotassic rocks in the West Kunlun is related to various amounts of sediments involved in mantle source. According to Chi et al. (2006, 2009)'s studies, there are two Cenozoic potassium-ultrapotassic volcanic rock belts in Tibetan Plateau, i.e., Qiangtang-Nangqian-Dianxi belt and Gangdise belt. The peak age of the former magmatism is at 40-30Ma, and the rocks are characterized by high MgO, low CaO and $Al_2O_3$, Whilst the peak age of the latter magmatism is at 30-24Ma, and the rocks have low $SiO_2$ and MgO/CaO, and high CaO and $Al_2O_3$. They concluded that the former was derived from the sources containing phlogopite harzburgite previously metasomatized by Si-rich and potassium-rich fluid (melt), whereas the latter type was predominantly sourced from harzburgite. The adakitic volcanic rocks in Tibetan Plateau are commonly believed to be produced by partial melting of the thicken lower crust with garnet (Wei et al., 2005; Wang et al., 2005, 2008; Zhao et al., 2007; Dong et al., 2008).

Recent studies have yielded some new interpretation on the petrogenesis of late Eocene high-Mg potassic volcanic rocks from "Shanjiang" area adjacent to the eastern Tibetan Plateau. Huang et al. (2007) suggested that the primary magma was likely generated from partial melting of spinel harzburgitic source metasomatized by Paleo-Tethys subduction-related fluid, and the high-Mg magmas had undergone fractional crystallization and accumulation of olivines in a deep-level magma chamber, whereas the fractional crystallization of feldspar and clinpyroxene in relatively shallow-level magma chamber extensively occurred in the evolution of the trachytes. Chen et al. (2008, 2010) also made a similar conclusion by comparing high-Mg potassium magmas from the "Shanjiang" with intra-Tibetan Plateau, southern and northern Tibetan Plateau, but the enriched degree and mineral compositions of the sources in these areas should be different.

One special type of volcanic rocks, kamafugite, in Li County, Gansu province, situated in the West Qinling, the eastern margin of Tibean Plateau, has been recognized. Many mantle peridotite xenoliths were found in kamafugite (Su et al., 2009). Although plenty of geochemical data on kamafugite have been carried out, its petrogenesis still remains debated. Yu et al. (2009) suggest that kamafugite was derived from a mixture of EM1, DMM and HIMU mantle endmembers, which may be related to mantle plume via. systematic geochemical study (major elements, trace elements and Sr-Nd-Pb isotope); whereas Dong et al. (2008) argued that the kamafugite was sourced from the mixture of EM2, DMM and HIMU endmembers. However, all of them believe that primitive magma is derived from deep mantle, i.e., there is a thick lithosphere lid beneath the area. Thus, some important questions concerning the petrogenesis of kamafugite may be raised: why kamafugite occurred in this area rather than other areas? How does melilite form in kamafugite? why is melilite absent in other alkaline volcanic rocks? Which special source (mineral composition) are melilite-bearing alkaline volcanic rocks derived from?

## II. PROBLEMS AND SUGGESTIONS FOR FUTURE WORKS

1) Although the progresses and achievements on geochronology, petrology and geochemistry of the Cenozoic volcanic rocks are fruitful, there are not much original achievements, which could be related to the current scenario that our study mainly depend on geochemistry (including chronology) but not pay much attention on field geology and petrographic observation. We suggest that the close combination of field geology, petrography, physical chemistry of petrology (phase equilibrium, thermodynamics and chemical kinetics), experimental petrology, disequilibrium thermodynamics and elements-isotope geochemistry should be strengthened..

2) Magmatism in China has a characteristic feature, i.e., the volcanic rocks formed in a continent that results from multi-block matching during different times. We should focus on this special feature so that we can obtain some innovative achievements that are distinguishable from other countries.

3) Given the advantages of volcanic rocks formed different times, tectonic settings, and depth of the earth, some new results about structures, compositions and geodynamics of crust and mantle in different evolution stages of earth history would be produced via. systematic petrology and elemental-isotope geochemistry studies in combination with deep geophysical data.

4) Based on geology, it is necessary to further explore new geochemical techniques (e.g., dating techniques of Holocene volcanic rocks) and strengthen experimental petrology, which will play important role in the petrogenesis of volcanic rocks.

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# NEW ADVANCES IN STUDIES ON THE GEOCHEMISTRY OF HYDROTHERMAL FLUIDS IN CHINA

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ABSTRACT:Increasing attention has been paid to the role and importance of the fluids within the earth's interior. This paper reviewed the main advances in studies on the geochemistry of hydrothermal fluids obtained by researchers in China. In recent several years, significant advances have been made by Chinese researchers in the field of geochemistry of hydrothermal fluids. To sum up, major progress is shown in the following 5 aspects:

In aspect of volcanology, Zhao et al (2006) and Zhao (2008) systematically measured the chemical, helium and carbon isotopic compositions of gases escaped from the hot springs in Tengchong Volcanic Field (TVF), put forwarded a new concept of relative geothermal gradient, revealed the temperature field characteristics in the uppermost crust beneath TVF, demonstrated the spatial-temporal distribution pattern of mantle-derived volatiles release, discovered 3 magma chambers beneath TVF, and estimated the present temperature, sizes and depths of these 3 magma chambers. Shuangguan et al (2008) investigated the geochemical features of magmatic gases in the regions of dormant volcanoes in China. They believe that, the $CO_2$ is the main gas component derived from magma at the dormant volcanic regions in China, which volume percentage contents range from 80% to 99%, the trace gases $CH_4$ and He are the most important gas components, there is not immediate eruption risk for the Tianchi volcano, Changbai Mountains, northeast China. Shangguan et al (2006) investigated isotopic composition of and dynamic fractionation between carbon-bearing gases escaped from volcanic field in China. They believe that the main cause for the occurrence of methane with lower $\delta^{13}C$ value is dynamic isotope fractionation during the ascending migration of methane derived from the deep magma chamber, the more deeper the magma chamber, the lower the delta $\delta^{13}C$ value of methane. They put forward the correlation formula between the magma chamber depth and the methane $\delta^{13}C$ value, which is $d\ (km) = 0.\ 0107\ (\delta^{13}C)^2 + 1.14$ ( where d expresses the depth (km) of magma chamber, the $\delta^{13}C$, is the isotopic composition of methane). They suggest that the carbon isotope fractionation temperature between the carbon dioxide and methane derived from the mantle magma may be only the last reservoir depth of the gases, instead of the initial magma chamber depth.

In aspect of geothermics, Deng (2009) investigated the chemical and isotopic composition of the spring water and free gases in the Rehai Geothermal Field (RGF), She believe that the thermal reservoir fluids are mixed from 3 end-members which are deep Cl-rich water, $CO_2$-rich steam and meteoric water, there exists an obvious contribution of mantle water to thermal reservoir fluids and spring water, the age of meteoric water which form the main part of geothermal fluids are 10-36a, the $CO_2$ are mantle-derived. Deng (2009) also put forward a conceptual model of the thermal reservoir. Du et al (2005) discussed the geothermal variations, origins of carbon-bearing components and reservoir temperatures in RGF. They believe that the $CO_2$ probably has a mantle/magma origin, but $CH_4$ and He have multiple origins, $HCO_3^-$ and $CO_3^=$ in RGF thermal fluids are predominantly derived from igneous carbon dioxide, but other ions originate from rocks through which the fluids circulate, the best estimate of subsurface reservoir temperature may be 250-300℃.Shangguan et al (2005) investigated the evolution of over 20 hydrothermal explosions during the period 1993-2003 occurred at RGF. They found that there are three distinguishable stages of ever-increasing magnitude of the explosions which activity intensified with time, the source of the gases feeding the explosions has progressively shifted from shallower to greater depth, larger hydrothermal explosions will probably occur in the future, so that this hazard must be taken into serious consideration. Zhao et al (2004) put forwarded the conceptual model of hydrothermal explosion in RGF. They shown 4 type of hydrothermal explosion: (1) artificial drilling triggered well blow, (2) high temperature hydrothermal explosive eruption, (3) high temperature vapor explosive eruption and (4) sustained or intermittent fountain, which are transitional type from hydrothermal explosion to normal hot spring. They suggested that there exist 3 layers of thermal reservoirs in different depth, the magma chamber beneath RGF is the heat source of hydrothermal explosion, these explosions are not relative to seismicity and are normal geothermal energy release, not precursor of increasing activity of magma beneath RGF.

In aspect of environment, Zhang et al (2008) assessed possible impact on environment of As and Sb in hot spring waters in the Rehai and Ruidian geothermal fields. Their results show that, As and Sb in hot spring waters are in the range 43.6-687 μg/L and 0.38-23.8 μg/L, respectively, As(III) occurs in most spring waters, and constitutes up to 91% of the total As, a fraction of the geothermal As and Sb is trapped in the sinter deposits while most enters the environment, the diffusion of As and Sb into groundwater and downstream crop fields constitutes a threat to the health of the local population. Zhao K (2005) and Zhao K et al (2005) surveyed $CO_2$ degassing from hot springs on main faults in Yunnan Province, China, where there exist some 700 hot springs. They discussed the source of $CO_2$ and estimate the emission quantity of $CO_2$ in Yunnan, constructed release model of deep source $CO_2$ from hot spring water, and calculated $CO_2$ emission quantity of the 38 hot springs. They constructed the evaluation index system of $CO_2$ emission intensity of hot spring in Yunnan, and evaluate the $CO_2$ emission intensity of these 38 hot springs. Finally, they estimated the total $CO_2$ emission quantity of the 700 hot Springs, which is up to $6\times10^4$ t/a.

In aspect of tectonics, By helium-isotope mapping, Zhao (2008) believe that the spatial distribution pattern of mantle-derived volatiles release intensity present day is the direct reflection of size and strength of asthenosphere upwelling in the Tengchong volcanic field, which covers an area of 100km×50km. Shen LC et al (2007) demonstrated spatial variation patterns of helium isotope composition in southwest China and discussed its tectonic implications. They suggested that, the central and northern Tibet, are of strong compression and crust accretion tectonic setting, that the southwest Yunnan (especially Tengchong area), is of extension tectonic setting, and of the strongest mantle-degassing area and the most violent collision area between Indian and Eurasia plate, that central Yunnan (Xiaojiang fault), is of the furthest east extent of collision between Indian and Eurasia plate, and that west Sichuan (Xianshuihe fault), is cut by Xianshuihe fault through the whole lithosphere in part up to the upper mantle. Hou and Li (2004) systematically studied the isotopic geochemistry of helium emitted from geothermal springs in the southern Tibetan. They defines two kinds of principal helium variation domains, i.e., mantle helium domain(R/Ra=0.11-5. 38) and crustal helium domain (R/Ra=0.017-0.072). They found both two helium domains are bounded by longitude $89^0$E in EW-direction, but all bestride the Yarlung Zangbu suture in SN-direction. They proposed that the Indus continent is underthrusting obliquely northwards as a whole with an inconsistent underthrusting front, which shows different slab styles in two sides of 89°E; to the west of 89°E, the continental slab downgoing towards NNE in a gentle slope has probably passed the Yarlung Zangbu suture and reached to the Bangong-Nujing suture; while to the east of 89°E, underthrusting slab front, likely to tear down along the Yadong-Gulou rift valley, is downgoing in a steep slope, thus has not spanned the Yarlung Zangbu suture. Li et al (2005), from other point, discussed the characteristic of bright spots and low velocity-high conductivity layer in the upper crust in the southern Tibet. They suggested that the low velocity-high conductivity layer was composed of silicate magma rather than water fluid. Their research provide new evidences for exist of the partial melting layers. What's more, they discussed how the partial melting layer driving the active hydrothermal system to circulate and flow. At last, they defined the spatial distribution of the partial melting layer based on the distribution of hot springs and temperature field.

In aspect of earthquake genetic mechanism, Du et al (2006) discussed the relationship between the origins of gases from hot springs and seismisity in western part of Sichuan Province, Southwestern China. They suggested that helium from hot springs in fault zones of Xianshuihe (XFZ) and Longmenshan (LFZ) is partially derived from the mantle with a mixture of crustal and atmospheric helium, however, helium in the Anninghe fault zone (AFZ) is derived mainly from the crust with mixing of mantle and atmospheric helium, and that the carbon dioxide is predominately derived from the upper mantle except for Wenchuan (No.18), where a great M8.0 earthquake occurred at 12 May, 2008, which killed some 90 thousand peoples. They believed that the hot springs situated along the more active part of faults have higher temperatures, the more tectonically active the district is, the larger the $\delta^{13}C$ and $^{3}He/^{4}He$ values and the greater the frequency of earthquakes, and the local geothermal anomalies formed by upward migration of anatectic fluids that, in turn, contribute to the energy released through earthquakes. Their results on helium and carbon isotopes suggest that He and $CO_2$ in hot springs may be important geochemical markers for seismological and tectonic activity.

KEYWORDS: Hot Spring, Geothermal Fluids, Geochemistry, Helium Isotope, Carbon Isotope, Geothermometer, Relative Geothermal Gradient, Magma Chamber, Temperature, Geothermal Reservoir, Hydrothermal Explosion, Volcano, Earthquake, Environmental Impact, $CO_2$ Degassing, Carbon Cycle, Deep Fault, Tectonics, Partial Melting Layer, Underthrusting Front, Tibet, Sichuan, Yunnan, Tengchong

## I. INTRODUCTION

As widely well known, the solid earth is mainly constituted by many kinks of rocks that are comprised of various sorts of minerals, so the content and function of fluids within the earth's interior are neglected for a long time. By large number of studies on volcanic and geothermal area, the important role the fluids played in volcanism and geothermal activities have been widely accepted. Recently, Zhao et al (2010) synthesized information from recent high-resolution tomographic studies of large crustal earthquakes which occurred in the Japanese Islands during 1995-2008. Prominent anomalies of low-velocity and high Poisson's ratio are revealed in the crust and uppermost mantle beneath the mainshock hypocenters, which may reflect arc magma and fluids that are produced by a combination of subducting slab dehydration and corner flow in the mantle wedge. Distribution of 164 crustal earthquakes (M5.7-8.0) that occurred in Japan during 1885-2008 also shows a correlation with the distribution of low-velocity zones in the crust and uppermost mantle. A qualitative model is proposed to explain the geophysical observations recorded so far in Japan. They consider that the nucleation of a large earthquake is not entirely a mechanical process, but is closely related to the subduction dynamics and physical and chemical properties of materials in the crust and upper mantle, in particular, the arc magma and fluids. Zhao et al's (2010) result suggests fluids play also an important role in tectonic evolution and earthquake preparation. In addition, global warming and greenhouse gas emissions are becoming a problem which the human being must to meet. Except oceans, vegetation and soil, atmosphere, the earth's interior itself is an important carbon reservoir. Increasing attentions has been paid to $CO_2$ emission from earth's interior. Impacts on environment of toxic elements emitted from geothermal fluids also attracted some attention.

This paper reviews the main advances in studies on the geochemistry of hydrothermal fluids obtained by researchers in China in recent several years, demonstrates the major achievements of Chinese researchers in this fields to international counterparts.

## II. MAIN ADVANCES IN STUDIES ON CHEMICAL AND ISOTOPIC COMPOSITIONS OF GEOTHERMAL FLUIDS IN VOLCANIC FIELD

### *1. A New Concept of Relative Geothermal Gradient is Put Forward and the Temperature Field in the Upper-most Crust Beneath Some Volcanic Area is Demonstrated*

Employing predecessor's chemical data of hydrothermal fluids (hot springs), selecting unified geothermometer, Zhao et al (2006) calculate the temperature of thermal reservoirs beneath Tengchong volcanic field, Yunnan Province, China. Assuming that the depth of these thermal reservoirs are same, then the temperature difference between hot springs and thermal reservoirs is defined by Zhao et al (2006) as relative geothermal gradient. According to this definition, Zhao et al (2006) calculate the values of relative geothermal gradient in entire the Tengchong volcanic field. Using the values of relative geothermal gradient, the map of relative geothermal gradient in the entire Tengchong volcanic and adjacent areas is obtained with Kriging interpolation. According to this spatial distribution map and these data, Zhao et al (2006) study spatial distribution characteristics of the temperature field of the uppermost crust in the Tengchong volcano field, and discuss the relationship between the existence and the activity of magma chambers and the spatial distribution characteristics of the temperature field. It is discovered by Zhao et al (2006) that there exist 3 abnormal areas where relative geothermal gradient are higher than 100℃ in most upper crust beneath the Tengchong volcanic field. These 3 significant abnormal areas of relative geothermal gradient, resulting from thermo diffusion of magma chamber underneath them, may be regarded as thermal aureole(or cap) of magma chamber, and reflects the existence of 3 magma chambers indirectly.

### *2. The Geochemical Characteristics of the Hot Spring Waters in Some Geothermal Fields, and Their Possible Environmental Impact are Discussed*

The geochemical characteristics of the hot spring waters in the Rehai and Ruidian geothermal fields, Tengchong volcanic field, Yunnan Province, China are described and their possible environmental impact are assessed by Zhang et al (2008). Their results show that the alkaline spring waters contain high levels of K, Na, F, Cl, $SiO_2$, whereas the only acidic spring water in Rehai geothermal field contains high levels of $SO_4^{2-}$, Mn and Fe. As and Sb in the spring waters are in the range 43.6-687 μg/L and 0.38-23.8 μg/L, respectively. As(III) occurs in most spring waters, and constitutes up to 91% of the total As. A fraction of the geothermal As and Sb is trapped in the sinter deposits while most enters the environment. The diffusion of As and Sb into groundwater and downstream crop fields constitutes a threat to the health of the local population.

### *3. Evolution and Conceptual Model of Geothermal Reservoirs and Hydrothermal Explosions at Some Geothermal Field are Characterized in Detail*

The Rehai geothermal field is still very rich in active manifestations such as boiling spring, fumoroles and hydrothermal explosion and is of high significance due to its theoretical research value.

By investigating the chemical composition such as Cl, B, Na and other elements , isotopic composition such as $^{18}O$, D and $^{3}H$ of the spring water, Deng (2009) believe that these springs share a same deep thermal reservoir and which water is a mixture of thermal reservoir fluids and groundwater at different levels, that these thermal reservoirs share uniform supply source of water, and that thermal reservoir fluids are mixed from 3 end-members which are deep Cl-rich water, $CO_2$-rich steam and meteoric water. Deng (2009) identify that the geothermal field is recharged from the northern and eastern mountainous areas at altitude of 1600m to 2300m, and that there exists an obvious contribution of mantle water to thermal reservoir fluids and spring water. Deng (2009) also believe the age of meteoric water which form the main part of geothermal fluids are 10-36a. By investigating $\delta^{13}C$ of total dissolved carbon (TDC) in hot spring water and $CO_2$ escaped from the springs or fumaroles, which varies between -5‰ and 1.99‰, Deng (2009) believes the fractionation of $^{13}C$ between TDC and $CO_2$ is negligible, and estimates the $\delta^{13}C$ of $CO_2$ in deep thermal reservoir are -2-0‰, indicating these $CO_2$ are mantle-derived. Together employing diverse geothermometers of Na-K, $SiO_2$, $CO_2$-$CH_4$ etc, Deng (2009) put forward a conceptual model of the thermal reservoir. The reservoir can be recognized as two aquifers at different depth: the shallower one is about 250-320m subground with temperature of about 220~230℃and with very quick water circulation; the deeper one is at depth more than 660~785m with temperature of 270~280℃, and the temperature of deep fluid is about 400~450℃.

On the basis of carbon isotope compositions, combined with helium isotope ratios and geothermal data from 1973 to 2000, Du et al (2005) also discussed the geothermal variations, origins of carbon-bearing components and reservoir temperatures in the Rehai geothermal field. Their data shows the $\delta^{13}C$ values of $CO_2$, $CH_4$, $HCO_3^-$, $CO_3^=$ and travertine in the hot springs range from -7.6‰ to -1.18‰, -56.9‰ to -19.48‰, -6.7‰ to -4.2‰, -6.4‰ to -4.2‰ and -27.1‰ to +0.6‰, respectively. Du et al (2005) believe that the $CO_2$ probably has a mantle/magma origin, but $CH_4$ and He have multiple origins, $HCO_3^-$ and $CO_3^=$ in RGF thermal fluids are predominantly derived from igneous carbon dioxide, but other ions originate from rocks through which the fluids circulate. Illustrating the $\delta^{13}C$ values of $CO_2$, $HCO_3^-$ (aq) and $CO_3^=$ (aq), Du et al (2005) believe that isotopic equilibriums between $CO_2$ and $HCO_3^-$ (aq), and $CO_3^=$ (aq) and between dissolved ion carbon (DIC) and travertine were not achieved, and no carbon isotope fractionation between $HCO_3^-$ (aq) and $CO_3^=$ (aq) of the hot springs in RGF was existed. Employing various geothermometers, temperatures of the geothermal reservoirs are also estimated by Du et al (2005) which are in a wide range from 69℃ to 450℃ that fluctuated from time to time. Du et al (2005) believe that the best estimate of subsurface reservoir temperature may be 250-300℃, and that contributions of mantle fluids and shallow crust fluids in Rehai geothermal field varied with time, which resulted in variations of chemical and isotopic compositions and reservoir temperatures.

Shangguan et al (2005) investigated the evolution of over 20 hydrothermal explosions during the period 1993-2003 occurred at Rehai geothermal field. They found that, initially, the explosions occurred on the bed of the Zaotang River, and later along a NW-SE striking fault cross-cutting the river. The explosion activity intensified with time. The free gas samples collected from springs created by the explosions show $He^3/He^4$ ratios of 1.17, 2.22 and 4.05 Ra (Ra = $1.4\times10^{-6}$) for the three distinguishable stages of ever-increasing magnitude of the explosions, respectively. Data on helium isotopes and gas chemistry indicate that the source of the gases feeding the explosions has progressively shifted from shallower to greater depth. Following this trend, larger hydrothermal explosions will probably occur in the future, so that this hazard must be taken into serious consideration.

Zhao et al (2004) put forwarded the conceptual model of hydrothermal explosion in Rehai Geothermal Field (RGF). There exists an area covering some 1000 square meters (130m long and 70m wide) in RGF, where hydrothermal explosion occurs frequently. They shown 4 type of hydrothermal explosion: (1) artificial drilling triggered well blow, (2) high temperature hydrothermal explosive eruption, (3) high temperature vapor explosive eruption and (4) sustained or intermittent fountain, which are transitional type from hydrothermal explosion to normal hot spring. Hydrogeological settings survey, hydrogen and oxygen isotopes show that underground water stored in lava with porous structure is source of heat-loaded water which spend some 15 years to complete a convection from permeating through upper rock down to heat source and finally discharging in surface again, that the north-south or west-east trending strike-slip faults and preexisted lava eruption channels are conduits of heat fluid, and that kaolin-altered granite conglomerate is the cap rock of the thermal reservoir, and the precambrian Gaoligongshan schist, the thermal reservoir rock. The magma chamber beneath RGF is the heat source of hydrothermal explosion. There exist 3 layers of thermal reservoirs in different depth. They believe that these explosions are not relatives with seismicity and that these phenomena are normal geothermal energy release, not precursor of increasing activity of magma beneath RGF.

4. *Geochemical Features of Magmatic Gases in the Dormant Volcanic Regions in China and its Implications are Investigated*

Shuangguan et al (2008) investigated the geochemical features of magmatic gases in the regions of dormant volcanoes in China. They believe that, the $CO_2$ is the main gas component derived from magma at the dormant volcanic regions in China, the volume percentage contents range from 80% to 99%, and the trace gases are $CH_4$, He, $H_2$, $N_2$, Ar, $O_2$, $H_2S$, $SO_2$, CO etc., among them the $CH_4$ and He are the most important gas components derived from the mantle magma. They suggest that the $^3He/^4He$ ratio is the most reliable indicator of the mantle matter; and the carbon isotopic compositions ($\delta^{13}C$) of $CO_2$ and $CH_4$ derived from magma also distinguish significantly from the shallow gases. By monitoring the carbon isotopic fractionation between the $CO_2$ and $CH_4$, they suggest that, although the June 29, 2002 Wangqing, Jilin Ms 7.2 deep earthquake disturb the local mantle magma chamber, but a large-scale upwelling of mantle material would be not occurred, indicating that there is not immediate eruption risk for the Tianchi volcano, Changbai Mountains, northeast China.

5. *Helium-Isotope Mapping is Conducted and the Spatial-Temporal Distribution Pattern of Mantle-Derived Volatiles Release is Demonstrated in Tengchong Volcanic Field*

Zhao (2008) systematically collected gas samples escaped from hot springs in the Tengchong volcanic field employing the sample collecting instrument with atmosphere-contaminating-prevention and enrichment function. The gas samples which are used to analyze for helium isotope composition are packed in steel cylinder or glass bottle. With the gas chromatograph, conventional components are analyzed, and with the mass spectrometer (VG5400), $^3He/^4He$, $^4He/^{20}Ne$ are analyzed. Atmospheric contamination correction is made for $^3He/^4He$ ratio through the $^4He/^{20}Ne$ value. Then Zhao (2008) calculated percentage proportion of atmospheric, crustal and mantle helium. Finally the correction for percentage proportion of different source helium is performed. Employing Kriging interpolation, the plane distribution maps of primitive helium isotopic composition $^3He/^4He$ (Ra) ratio values, of corrected helium isotopic composition $^3He/^4He_c$ (Ra) ratio values, of percentage M which express contribution of mantle reservoir to helium isotopic composition, and of corrected percentage $M_c$ in entire the Tengchong volcanic and adjacent areas are obtained. These maps can reflect the spatial intensity level of mantle-derived volatiles release in the entire Tengchong volcanic and adjacent areas, and time series of these values of helium isotopic composition at the same localities can reflect time variations of mantle-derived volatiles release. Synthesizing specific data and these maps, Zhao (2008) studied spatial and temporal distribution characteristics of intensity of mantle-derived mass release in the entire Tengchong volcanic and adjacent areas, discusses the relationship between the existence and activity of magma chambers and these spatial and temporal distribution characteristics. Zhao's (2008) dada show that there exist 3 separable different regions where intensity of mantle-derived volatiles release is abnormally higher, their $^3He/^4He$ (Ra) ratio values are more than 5.5Ra, 4.5Ra, and 2Ra, respectively, and their corresponding percentage proportion of mantle source are more than 70%, 60%, and 30%, respectively. These 3 mantle-derived volatiles strong release regions overlap on the 3 significant relative geothermal gradient abnormal areas (see above section Ⅱ.1), further suggesting that there exist 3 magma chambers beneath the Tengchong volcano area. Zhao (2008) believe that the spatial distribution pattern of mantle-derived volatiles release intensity present day is the direct reflection of size and strength of asthenosphere upwelling in the Tengchong volcanic area, which covers an area of 100km×50km. This local upwellinged asthenosphere either provides matter source of magma for the Tengchong volcano to prepare or results in the crust extension which provides structural conduits for magma to migrate up. The crust extension in the Tengchong volcanic area predicted with this model is also supported by today's local geomorphological investigation and deformation observation.

6. *Isotopic Composition of，Dynamic Fractionation Between Carbon-Bearing Gases Escaped from Volcanic Field in China and the Temperature of Magma Chambers are Discussed in Detail*

Shangguan et al (2006) investigated isotopic composition of and dynamic fractionation between carbon-bearing gases escaped from volcanic field in China. They found that, the mean $\delta^{13}C$ values of methane for 22 springs from the Tengchong volcanic area and 11 springs from the Changbaishan Tianchi volcanic area (except Hubin springs) are -19.0‰(PDB) and -32.6‰(PDB) respectively, similar to that from worlds geothermal area, but the mean $\delta^{13}C$ values of methane at the Wudalianchi volcanic area and the Hubin strong gas discharge region located within the Tianchi crater lake are -45.8‰(PDB) and - 47.9‰(PDB) respectively, much lower than that of other volcanic area in China, and similar to that from the lake Kivu in the Eastern Africa. They suppose that such methane could be directly derived from the upper mantle, and the main cause for the occurrence of methane with lower $\delta^{13}C$ value is dynamic isotope fractionation during the ascending migration of methane derived from the deep magma chamber, the more deeper the magma chamber, the lower the delta $\delta^{13}C$ value of methane. They put forward the correlation formula between the magma chamber depth and the methane $\delta^{13}C$ value, which is $d\ (km) = 0.0107\ (\delta^{13}C)^2 + 1.14$ ( where d expresses the depth (km) of magma chamber, the $\delta^{13}C$, is the isotopic composition of methane). They suggest that the carbon isotope fractionation temperature between the carbon dioxide and methane derived from the mantle magma may be only the last reservoir depth of the gases, instead of the initial magma chamber depth.

Zhao (2008), employing the sample collecting instrument with atmosphere-contaminating-prevention and methane-enrichment function, collected gas samples escaped from hot springs within 3 overlapping abnormal areas (magmatically active region) in the Tengchong volcanic field, where both the intensity of relative geothermal gradient (see above section Ⅱ.1) and mantle-derived volatiles release (see above section Ⅱ.5) are significant. The gas samples which are used to analyze conventional component and carbon isotope composition are packed in aluminum-film-covered plastic bags. Zhao

(2008) carries on enrichment of $CH_4$ for carbon isotope sample at site, analyzes carbon isotope composition of both $CO_2$ and $CH_4$ sample with the mass spectrometer (MAT251). Choosing the most reasonable equilibrium fractionation equation or formula regressed from carbon isotope equilibrium fractionation factors of $CO_2$ and $CH_4$ which were theoretically calculated or experimentally determined, Zhao (2008) calculates the temperature of gas source area (magma chambers). Zhao's (2008) results show that the temperatures of central magma chambers possibly in 700-1200℃, which has achieved the formation temperature of rhyolite magma (600-900℃), andesite magma (800-1100℃) and basalt magma (1000-1250℃), further suggesting the objective existence of the 3 magma chambers at present beneath the Tengchong volcanic field.

7. *Integrated Analysis of Existence and Activities of Magma Chambers in Tengchong Volcanic Field are Conducted and Model of Mechanism of Tengchong Volcano is Put Forward*

Based on the above data (see section Ⅱ.1, 5, and 6), by resolving theses 3 issues such as temperature field in most upper crust, mantle-derived volatiles release field, and temperature of magma chamber, and combining achievements in deep sounding (DSS and MT), activity monitory and origin research that the former investigators obtained, Zhao (2008) obtains the following understandings on Tengchong volcanic field:

*(1).* There exist 3 magma chambers in crust present day in the Tengchong volcanic field. The 1st one is located Tengchong county-Heshun township-Rehai resort area where is the center of the Tengchong volcanic field. The 2nd one is located Qushi-Mazhan area where is in northern of the Tengchong volcanic field. The 3rd one, lies in Wuhe-Puchuan-Xinhua area where is in southern of the Tengchong volcanic field. The relative geothermal gradients in the upper-most crust above the 3 magma chambers are 140℃, 120℃, 130℃, respectively. The mantle-derived proportions of volatile mass release of the 3 magma chambers are 70%, 60% and 30%, respectively.

*(2).* The sizes (the horizontal diameter) of the 3 magma chambers are approximately 20km, 19km and 23 km (long 45km), respectively, the depths of them are different: the 1st is at 5-25km, the 2nd is 10-25km, and the 3rd is 7-14km.

*(3).* The temperature of the 1st magma chamber is within 324-789℃, with average 555℃. That of the 2nd one, within 402-663℃, with average 532℃, That of the 3rd one is within 320-1194℃, with average 679℃. It is believed that variation range of the present temperature of the gas enrichment region which is crown of magma chamber below the Tengchong volcanic field is 320-1200℃, the actual temperature of magma chamber should be higher than the mean value 600℃. The temperatures of margin area of these 3 magma chambers possibly are in 300-600℃, that of central part possibly, in 700-1200℃. The nowadays temperatures of these 3 magma chamber's center has achieved the formation temperature of rhyolite magma (600-900℃), the andesite magma (800-1100℃) and basalt magma (1000-1250℃), further suggesting the objective existence of these 3 magma chambers at present in the Tengchong volcanic field.

*(4).* The activities of these 3 magma chambers are different. The 1st one, collecting relative geothermal gradient, the mantle-derived volatiles release, the crust deformation and the seismicity and so on abnormal in one, being accepting the feeding from mantle-derived magma, is of strongest activity, and is located directly under the Tengchong county. Because its eruption will cause the most serious losses, so it needs emphasis surveillance. The 2nd one, where the release intensity of mantle-derived volatiles is also noticeable, which is also possibly accepting the feeding from mantle-derived magma, should be reinforced in monitoring. The 3rd one, which has the biggest size, and seats at the shallowest

depth, where the mantle-derived volatiles releases is weakest (30%), possibly accepting weakly feeding of the mantle-derived magma at present, but still with very high temperature, must be paid some attention.

*(5).* Local asthenosphere upwelling results in the formation of the Tengchong volcano. The local asthenosphere upwelling is possibally related with the slab break off of the ancient Nujiang oceanic lithosphere or/and the ancient Myitkyina oceanic lithosphere, but the eruption of Tengchong volcano is far later than the subduction of the two ancient oceanic lithosphere. Therefore it can be considered that the formation of the Tengchong volcano is not related with the normal tectonic plate subduction. The spatial distribution pattern of mantle-derived volatiles release intensity present day in the Tengchong volcanic field is the direct reflection of size and strength of this asthenosphere upwelling which covers 100km long from north to south, 50km wide from west to east approximately. This local upwelling asthenosphere either provides source of magma for the Tengchong volcano to prepare or results in the crust extension which provides structural conduits for magma to migrate up. The crust extension in the Tengchong volcanic area predicted with this model is also supported by today's local geomorphological investigation and deformation observation.

## III. MAIN ADVANCES IN STUDIES ON CHEMICAL AND ISOTOPIC COMPOSITIONS OF GEOTHERMAL FLUIDS IN NONVOLCANIC AREA

### *1. $CO_2$ Degassing from Hot Spring in Some Region is Investigated and Non-Anthropogenic Carbon Emission Quantity is Estimated*

Zhao K (2005) and Zhao K et al (2005) survey $CO_2$ degassing from 38 hot springs on main faults in Yunnan Province, China, where there exist some 700 hot springs, is one of the provinces in which there are the largest number of hot springs and strong earthquakes. They measure the temperature, pH value, $HCO_3^-$ content of hot spring water and $CO_2$ content in air around hot spring in site, collect free gas sample escaped from, total dissolved carbon (TDC) sample (site precipitation with NaOH and BaCl) in, and travertine sample precipitated from hot spring water and hot spring water its self in site, have chemical and carbon and or helium isotope composition of these sample analyzed in professional laboratory, calculate the $CO_2$ partial pressure ($P_{CO2}$) and saturation index of calcite (SIC) of hot spring water with software. By analyzing geology setting, environment condition, chemistry of water, carbon and helium isotope composition data, they discuss the source of $CO_2$ and estimate the emission quantity of $CO_2$ in Yunnan. They believe that, in east Yunnan, $CO_2$ mainly degassed from crust, and the tertiary coal (lignite) have an important contribution to $CO_2$ emissions, in northwest Yunnan, $CO_2$ mainly degassed from mantle and partly from crustal carbonate metamorphism, in southwest Yunnan, almost all $CO_2$ degassed from mantle. They construct release model of deep source $CO_2$ from hot spring water, and calculate $CO_2$ emission quantity of the 38 hot Springs, which vary from the minimum 0.0017 t/a to the maximum 1034 t/a, with average value 103.57 t/a. Employing these 38 hot spring data, they construct the evaluation index system of $CO_2$ emission intensity of hot spring in Yunnan, and evaluate the $CO_2$ emission intensity of these 38 hot spring. Finally, according division of the Cenozoic tectonic units and major deep faults distribution, they classify the 700 hot spring into several types of emission intensity, and by these intensity types, estimate the total $CO_2$ emission quantity of the 700 hot Springs, which is up to $6\times10^4$ t/a.

### *2. The Tectonic Implications of Hydrothermal Fluids Activity in Southwest China are Investigated*

Shen LC et al (2007) systematically collected typical gas-rich hot spring water samples in Tibet, Yunnan and west Sichuan and analyzed chemical and helium isotopic composition of gas dissolved in these water samples. According geochemical characteristics, especially helium isotope composition of these gases from the fault belts, they investigated the intensity of gas release of these $CO_2$ degassing point, especially the intensity of deep (mantle-derived) gas release. They demonstrated spatial variation patterns of helium isotope composition in southwest China and discussed its tectonic implications. They believe that, the central and northern Tibet, from where only 1.4%-1.7% mantle-derived helium escaped, in which the faults are tightly closed in the deep, are of strong compression and crust accretion tectonic setting, that the southwest Yunnan (especially Tengchong area), from where averagely 26.2%, most up to 48.8%, mantle-derived helium escaped, in which mantle-derived magma intrude into shallow crust, is of extension tectonic setting, the strongest mantle-degassing area and the most violent collision area between Indian and Eurasia plate, that central Yunnan (Xiaojiang fault), from where averagely 2.27%, most only 8.9%, mantle-derived helium escaped, is of the furthest east extent of collision between Indian and Eurasia plate, and that west Sichuan (Xianshuihe fault), from where averagely 8.1% mantle-derived helium escaped, more than in Tibet and the rest of Yunnan, but much less than in southwest Yunnan, is cut by Xianshuihe fault through the whole lithosphere in part up to the upper mantle.

Hou and Li (2004) systemically studied the isotopic geochemistry of helium emitted from geothermal springs in the southern Tibetan in order to get deep information on the Tibetan collision orogen, and to constrain the orogeny processes during Indus-Asian continental collision. They defines two kinds of principal helium variation domains, i.e., mantle helium domain(R/Ra=0.11-5. 38) and crustal helium domain (R/Ra=0.017-0.072). They shown that, the former mainly distributes in the Tengchong Rehai geothermal field (R/Ra=0. 40-5.38) near the eastern Himalayan syntax, the Shiquanhe geothermal field (R/Ra=0.27-0.30) near the western Himalayan syntax, and the Lhasa hydrothermal activity zone (R/ Ra=0.11-0.98) to the east of longitude 89°E, that the latter mainly present in the Ngamring hydrothermal activity zone(R/Ra=0.017- 0.072) to the west of 89°E; near the eastern and western syntaxes, where the hydrothermal activities is controlled by large-scale strike-slip faults, there are <50% mantle-derive helium's contribution in geothermal helium, that while in the hinterland of the plateau, where NS-trending rift control the development of hydrothermal zone, the value of R/Ra has obvious variation in east-west direction rather than in south-north direction. They found both two helium domains are bounded by longitude $89^0$E in EW-direction, but all bestride the Yarlung Zangbu suture in SN-direction. By synthetically analyzing the helium isotopic data and available geophysical data, they believe that modern hydrothermal activity was mainly driven by magmatic chambers or partially molten layers occurring as patches in the upper crust, but the contribution of mantle heat and mass (helium) to spring gases has been recognized to the east of 89°E. As a consequence, they proposed that the Indus continent is underthrusting obliquely northwards as a whole with an inconsistent underthrusting front, which shows different slab styles in two sides of 89°E; to the west of 89°E, the continental slab downgoing towards NNE in a gentle slope has probably passed the Yarlung Zangbu suture and reached to the Bangong-Nujing suture; while to the east of 89°E, underthrusting slab front, likely to tear down along the Yadong-Gulou rift valley, is downgoing in a steep slope, thus has not spanned the Yarlung Zangbu suture.

Based on the research on the violent hydrothermal activity of the south Tibet, Li et al (2005), from other point, discussed the characteristic of bright spots and low velocity-high conductivity layer which was recognized in the upper crust in the southern Tibet by a series of geophysical probe. After researching helium isotope composition of hot spring’s gas, geochemical characteristic of spring water, and former modeling for temperature field, they suggested that the low velocity-high conductivity layer was composed of rather silicate magma than water fluid. Their research provide new evidences for exist of the partial melting layers. What's more, they discussed how the partial melting layer driving the active hydrothermal system to circulate and flow. At last, they defined the spatial distribution of the partial melting layer based on the distribution of hot springs and temperature field.

3. *Helium and Carbon Isotopic Compositions of Thermal Springs in the Earthquake Zone of Sichuan, Southwestern China is Investigated and its Seismogenic Implication is Discussed*

Du et al (2006) collected samples of spring water and gas from the western part of Sichuan Province , Southwestern China and analyzed for isotope compositions of carbon. In terms of helium and carbon isotopes and energy released by earthquakes, they discussed the origins of gases from hot springs and earthquake activity in this area. Their data shows that the $\delta^{13}C$ values of carbon dioxide from hot springs in three earthquake zones of Xianshuihe, Anninghe and Longmenshan in Western Sichuan have a range of -3.34 to -17.09‰, and $^3He/^4He$ ratios exhibit a wide range from $1.5\times10^{-8}$ to $3.63\times10^{-6}$. They found that the different earthquake and/or fault zones are of different isotopic features of helium and carbon, and different parts of the same zone also differ in terms of isotopic compositions. They suggested that helium from hot springs in fault zones of Xianshuihe (XFZ) and Longmenshan (LFZ) is partially derived from the mantle with a mixture of crustal and atmospheric helium, however, helium in the Anninghe fault zone (AFZ) is derived mainly from the crust with mixing of mantle and atmospheric helium, and that the carbon dioxide is predominately derived from the upper mantle except for Wenchuan (No.18), where a great M8.0 earthquake occurred at 12 May, 2008, which killed some 90 thousand peoples. They believed that the hot springs situated along the more active part of faults have higher temperatures, the more tectonically active the district is, the larger the $\delta^{13}C$ and $^3He/^4He$ values and the greater the frequency of earthquakes, and the local geothermal anomalies formed by upward migration of anatectic fluids that, in turn, contribute to the energy released through earthquakes. Their results on helium and carbon isotopes suggest that He and $CO_2$ in hot springs may be important geochemical markers for seismological and tectonic activity.

## IV. SUMMARY

In recent several years, significant advances have been made by Chinese researchers in the field of geochemistry of hydrothermal fluids. To sum up, major progress is shown in the following 5 aspects:

In aspect of volcanology, Zhao et al (2006) systematically measured the chemical, helium and carbon isotopic compositions of gases escaped from the hot springs in Tengchong volcanic field, put forwarded a new concept of relative geothermal gradient, revealed the temperature field characteristics in the uppermost crust beneath Tengchong volcanic field, and discovered 3 abnormal areas where relative geothermal gradient is significant higher. Zhao (2008) conducted helium-isotope mapping in Tengchong volcanic field, demonstrated the spatial-temporal distribution pattern of mantle-derived volatiles release, and discovered 3 separable different regions where intensity of mantle-derived volatiles release is abnormally higher. According that these 3 mantle-derived volatiles strong release regions overlap on the 3 significant relative geothermal gradient abnormal areas, Zhao (2008) found that there exist 3 magma chambers beneath the Tengchong volcanic field. Zhao (2008) also measured the carbon isotope fractionation coefficient between $CO_2$ and $CH_4$ of free gas sample collected from hot springs in the above these 3 magma chambers, by which the present temperature of these 3 magma chambers are estimated up to 700-1200℃. In addition, Zhao (2008) also estimated the important parameters such as sizes, depths s of these 3 magma chambers, and assessed the activities of them. Shuangguan et al (2008) investigated the geochemical features of magmatic gases in the regions of dormant volcanoes in China. They believe that, the $CO_2$ is the main gas component derived from magma at the dormant volcanic regions in China, which volume percentage contents range from 80% to 99%, the trace gases $CH_4$ and He are the most important gas components, there is not immediate eruption risk for the Tianchi volcano, Changbai Mountains, northeast China. Shangguan et al (2006) investigated isotopic composition of and dynamic fractionation between carbon-bearing gases escaped from volcanic field in China. They believe that the main cause for the occurrence of methane with lower $\delta^{13}C$ value is dynamic isotope fractionation during the ascending migration of methane derived from the deep magma chamber, the more deeper the magma chamber, the lower the delta $\delta^{13}C$ value of methane. They put forward the correlation formula between the magma chamber depth and the methane $\delta^{13}C$ value, which is $d\ (km) = 0.\ 0107\ (\delta^{13}C)^2 + 1.14$ ( where d expresses the depth (km) of magma chamber, the $\delta^{13}C$, is the isotopic composition of methane). They suggest that the carbon isotope fractionation temperature between the carbon dioxide and methane derived from the mantle magma may be only the last reservoir depth of the gases, instead of the initial magma chamber depth.

In aspect of geothermics, Deng (2009) investigated the chemical and isotopic composition of the spring water and free gases in the Rehai geothermal field, She believe that the thermal reservoir fluids are mixed from 3 end-members which are deep Cl-rich water, $CO_2$-rich steam and meteoric water, there exists an obvious contribution of mantle water to thermal reservoir fluids and spring water, the age of meteoric water which form the main part of geothermal fluids are 10-36a, the fractionation of $^{13}C$ between total dissolved carbon (TDC) and $CO_2$ is negligible, the $\delta^{13}C$ of $CO_2$ in deep thermal reservoir are -2-0‰(PDB), these $CO_2$ are mantle-derived. Together employing diverse geothermometers of Na-K, $SiO_2$, $CO_2$-$CH_4$ etc, Deng (2009) put forward a conceptual model of the thermal reservoir. The reservoir can be recognized as two aquifers at different depth: the shallower one is about 250-320m subground with temperature of about 220~230℃and with very quick water circulation; the deeper one is at depth more than 660~785m with temperature of 270~280℃, and the temperature of deep fluid is about 400~450℃. Du et al (2005) also discussed the geothermal variations, origins of carbon-bearing components and reservoir temperatures in the Rehai geothermal field. They believe that the $CO_2$ probably has a mantle/magma origin, but $CH_4$ and He have multiple origins, $HCO_3^-$ and $CO_3^=$ in RGF thermal fluids are predominantly derived from igneous carbon dioxide, but other ions originate from rocks through which the fluids circulate, the isotopic equilibriums between $CO_2$ and $HCO_3^-$ (aq), and $CO_3^=$ (aq) and between dissolved ion carbon (DIC) and travertine were not achieved, and no carbon isotope fractionation between $HCO_3^-$ (aq) and $CO_3^=$ (aq) of the hot springs in RGF was existed, the temperatures of the geothermal reservoirs are in a wide range from 69℃ to 450℃ that fluctuated from time to time, the best estimate of subsurface reservoir temperature may be 250-300℃. Shangguan et al (2005) investigated the evolution of over 20 hydrothermal explosions during the period 1993-2003 occurred at Rehai geothermal field. They found that there are three distinguishable stages of ever-increasing magnitude of the explosions which activity intensified with time, the source of the gases feeding the explosions has progressively shifted from shallower to greater depth, larger hydrothermal explosions will probably occur in the future, so that this hazard must be taken into serious consideration. Zhao et al (2004) put forwarded the conceptual model of hydrothermal explosion in Rehai Geothermal Field (RGF). They shown 4 type of hydrothermal explosion: (1) artificial drilling triggered well blow, (2) high temperature hydrothermal explosive eruption, (3) high temperature vapor explosive eruption and (4) sustained or intermittent fountain, which are transitional type from hydrothermal explosion to normal hot spring. They suggested that there exist 3 layers of thermal reservoirs in different depth, the magma chamber beneath RGF is the heat source of hydrothermal explosion, these explosions are not relative to seismicity and are normal geothermal energy release, not precursor of increasing activity of magma beneath RGF.

In aspect of environment, Zhang et al (2008) assessed possible impact on environment of As and Sb in hot spring waters in the Rehai and Ruidian geothermal fields. Their results show that, As and Sb in hot spring waters are in the range 43.6-687 μg/L and 0.38-23.8 μg/L, respectively, As(III) occurs in most spring waters, and constitutes up to 91% of the total As, a fraction of the geothermal As and Sb is trapped in the sinter deposits while most enters the environment, the diffusion of As and Sb into groundwater and downstream crop fields constitutes a threat to the health of the local population. Zhao K (2005) and Zhao K et al (2005) survey $CO_2$ degassing from hot springs on main faults in Yunnan Province, China, where there exist some 700 hot springs. By analyzing geology setting, environment condition, chemistry of water, carbon and helium isotope composition data, they discuss the source of $CO_2$ and estimate the emission quantity of $CO_2$ in Yunnan. They construct release model of deep source $CO_2$ from hot spring water, and calculate $CO_2$ emission quantity of the 38 hot springs, which vary from the minimum 0.0017 t/a to the maximum 1034 t/a, with average value 103.57 t/a. Employing these 38 hot spring data, they construct the evaluation index system of $CO_2$ emission intensity of hot spring in Yunnan, and evaluate the $CO_2$ emission intensity of these 38 hot spring. Finally, according division of the Cenozoic tectonic units and major deep faults distribution, they classify the 700 hot spring into several types of emission intensity, and by these intensity types, estimate the total $CO_2$ emission quantity of the 700 hot Springs, which is up to $6\times10^4$ t/a.

In aspect of tectonics, By helium-isotope mapping, Zhao (2008) believe that the spatial distribution pattern of mantle-derived volatiles release intensity present day is the direct reflection of size and strength of asthenosphere upwelling in the Tengchong volcanic field, which covers an area of 100km×50km. Shen LC et al (2007) demonstrated spatial variation patterns of helium isotope composition in southwest China and discussed its tectonic implications. They suggested that, the central and northern Tibet, are of strong compression and crust accretion tectonic setting, that the southwest Yunnan (especially Tengchong area), is of extension tectonic setting, and of the strongest mantle-degassing area and the most violent collision area between Indian and Eurasia plate, that central Yunnan (Xiaojiang fault), is of the furthest east extent of collision between Indian and Eurasia plate, and that west Sichuan (Xianshuihe fault), is cut by Xianshuihe fault through the whole lithosphere in part up to the upper mantle. Hou and Li (2004) systematically studied the isotopic geochemistry of helium emitted from geothermal springs in the southern Tibetan in order to get deep information on the Tibetan collision orogen, and to constrain the orogeny processes during Indus-Asian continental collision. They defines two kinds of principal helium variation domains, i.e., mantle helium domain(R/Ra=0.11-5. 38) and crustal helium domain (R/Ra=0.017-0.072). They found both two helium domains are bounded by longitude $89^0$E in EW-direction, but all bestride the Yarlung Zangbu suture in SN-direction. They proposed that the Indus continent is underthrusting obliquely northwards as a whole with an inconsistent underthrusting front, which shows different slab styles in two sides of 89°E; to the west of 89°E, the continental slab downgoing towards NNE in a gentle slope has probably passed the Yarlung Zangbu suture and reached to the Bangong-Nujing suture; while to the east of 89°E, underthrusting slab front, likely to tear down along the Yadong-Gulou rift valley, is downgoing in a steep slope, thus has not spanned the Yarlung Zangbu suture. Li et al (2005), from other point, discussed the characteristic of bright spots and low velocity-high conductivity layer in the upper crust in the southern Tibet. They suggested that the low velocity-high conductivity layer was composed of silicate magma rather than water fluid. Their research provide new evidences for exist of the partial melting layers. What's more, they discussed how the partial melting layer driving the active hydrothermal system to circulate and flow. At last, they defined the spatial distribution of the partial melting layer based on the distribution of hot springs and temperature field.

In aspect of earthquake genetic mechanism, Du et al (2006) discussed the relationship between the origins of gases from hot springs and seismisity in western part of Sichuan Province, Southwestern China. They suggested that helium from hot springs in fault zones of Xianshuihe (XFZ) and Longmenshan (LFZ) is partially derived from the mantle with a mixture of crustal and atmospheric helium, however, helium in the Anninghe fault zone (AFZ) is derived mainly from the crust with mixing of mantle and atmospheric helium, and that the carbon dioxide is predominately derived from the upper mantle except for Wenchuan (No.18), where a great M8.0 earthquake occurred at 12 May, 2008, which killed some 90 thousand peoples. They believed that the hot springs situated along the more active part of faults have higher temperatures, the more tectonically active the district is, the larger the $\delta^{13}C$ and $^3He/^4He$ values and the greater the frequency of earthquakes, and the local geothermal anomalies formed by upward migration of anatectic fluids that, in turn, contribute to the energy released through earthquakes. Their results on helium and carbon isotopes suggest that He and $CO_2$ in hot springs may be important geochemical markers for seismological and tectonic activity.

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