The magma evolution of Tianchi volcano, Changbaishan*

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Abstract The Changbaishan Tianchi volcano is composed of the basaltic rocks at the shield-forming stage, the trachyte and pantellerite at the cone-forming stage and modern eruption. Studies on their REE, incompatible elements and Sr, Nd, Pb isotopes suggest that rocks at different stages have a common magma genesis and close evolution relationship with differentiation crystallization playing the key role. The co-eruption of basaltic trachyandesite magma and pantellerite magma indicates that there exist both crustal magma chamber and mantle magma reservoir beneath the Tianchi volcano.

Keywords: Changbaishan Tianchi volcano, petrology, geochemistry, magma evolution.

Although the study of Changbaishan Tianchi volcano may date back to the last century, the research on its petrology, chronology and geochemistry was mostly carried out in the 1980s[1—7]. The Changbaishan area, with Tianchi volcano as its center, is covered by large area of Cenozoic basalts with distribution of geological ages from early Tertiary to late Quaternary (fig. 1). This paper does not intend to discuss the petrology and geochemistry of Cenozoic volcanic rocks for the whole Changbaishan area but to focus on discussion of the problem of petrology, geochemistry and magma evolution of various rocks formed during the shield-forming, cone-forming stage and modern eruption stage of the Tianchi volcano itself.

1 Basalts at the shield-forming stage of Tianchi volcano

The basalts at the shield-forming stage of Tianchi volcano mainly refer to the basalt shield forming the base of the Tianchi volcanic cone, with its main part called Junjianshan basalt, mainly distributed over the Helong, Yanji, Antu, Changbai areas around the Tianchi volcano with the geological period between 4.5 and 2.1 Ma[1]. There is either trachyte of alkalic series or tholeiite and basaltic andesite in the basalt of Junjianshan period (see fig. 2). Jin et al. referred to the basalt located beneath the trachyte at the lowest part of the Tianchi volcano cone as Baishan basalt and Tumen River basalt, while Liu referred to it as Guangping basalt with its period between 1.66 and 1.48 Ma[7].

One of the remarkable features of the major element of basaltic rocks in the shield-forming stage is the high content of K_2O. Another remarkable feature is the low Mg content and extraordinarily low Ni content. This shows a significant contrast with the Cenozoic basalt of Northeast

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and North China areas, which has the higher content of MgO and Ni, indicating that the rocks of basalt during the shield-forming stage, either of alkalic series or of tholeiite series, are not the erupted materials from the original mantle basalt magma, but come from the evoluted magma contained in the mantle magma reservoir.

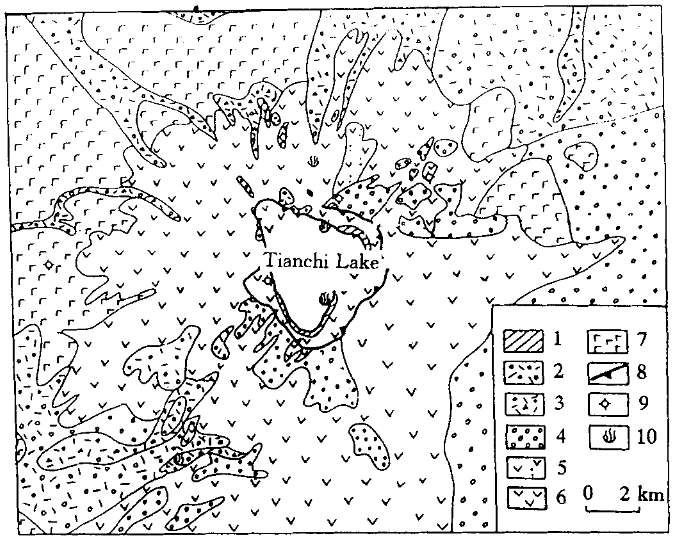

Fig. 1. Geological map of Changbaishan Tianchi volcano. 1, Historical eruption deposits; 2, ignimbrite sheet; 3, ignimbrite flow; 4, airfall deposits; 5, pantellerite clastogenetic lava; 6, pantellerite-trachyte composite-cone; 7, basaltic lava shield; 8, crater; 9, volcanic cone; 10, hot spring.

2 Rock composition of the Tianchi volcano cone

The cone of Tianchi volcano located above the basalt shield of Pliocene to early Pleistocene is composed mainly of trachyte and pantellerite lava and their pyroclasts, whose K-Ar age is within 1.12—0.04 Ma[8]. According to the period of eruption and the clay weathering layers formed by intermittent eruptions, Jin et al. (1994) divided the volcano cone into four stages of eruption. The volcano cone is composed mainly of aegirine trachyte or aegirine-quartz trachyte with total thickness of 1000 m, except the presence of riebeckite pantellerite at the fourth stage. About at the time between the third stage and the fourth stage, there were eruptions of trachybasalt consisting of red, purple red and brown red slag basalt and downward gradually becoming dark basalt, and most of them appeared at the slope of Tianchi volcanos cone as paresitic volcano. These basalts are shown in fig. 2 as trachybasalt, similar to shield-forming basalt in composition.

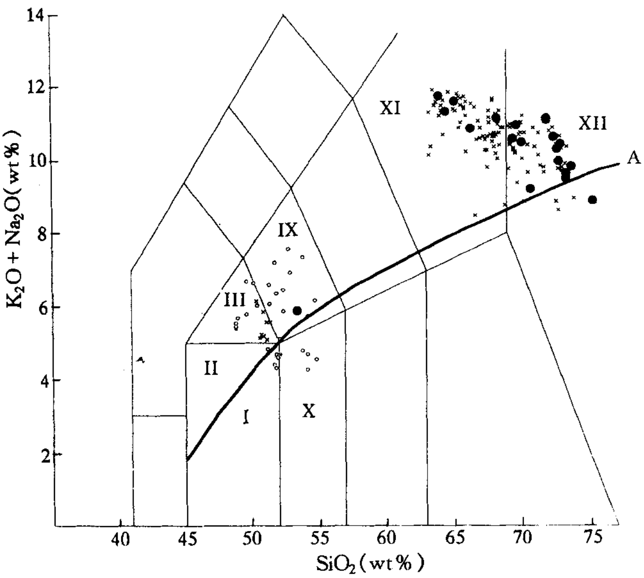

Fig. 2. TAS diagram of Changbaishan Tianchi volcanic rocks (based on Le Bas et al., 1986). 196 data provided by Zhang Ming, Liu Ruoxin, Zheng Xiangshen, partly cited from Jin Bolu et al. (1994). Line A is the boundaries line for alkaline and nonalkaline rocks (Miyashiro, 1978). I, Tholiite; II, alkaline basalt; III, trachybasalt; IX, basaltic trachyandesite; X, basaltic andesite; XI, trachyte; XII, rhyolite.

The phenocrysts in the pyroxene-quartz trachyte at the lower part of the cone are sanidine or anorthoclase, plagioclase and hedenbergite, sometimes a small amount of amphible and fayalite, with matrix consisting mainly of plagioclase and alkaline feldspar, also quartz and a small amount of amphible and scaly metabiotite. The phenocryst minerals in the aegirine•augite or hedenbergite and an even smaller amount of fayalite and arfvedsonite, but a small amount of plagioclase phenocryst still can be seen. Sometimes plagioclase occurs in rounded shape in other minerals. All the accessory minerals in the trachyte are titanic magnetite and apatite. Phenocrysts in pantellerite are mainly anorthoclase and aegirine, secondly are arfvedsonite and fayalite, quartz, the matrix of pantellerite is mostly glassy materials, some of them forming hair crystalline aggregate.

Some round-shaped small inclusions of fine-grained gabbro with a diameter of 1 mm in the aegirine-quartz-alkaline feldspar trachyte have been observed at the upper part of the cone. The existence of this kind of fine-grained gabbro inclusion and anorthoclase, aegirine, arfvedsonite, quartz and fayalite phenocryst universally present in the trachyte and pantellerite suggests that crystalline differentiation of different evolution stages has occurred in the magma chamber. The earliest one crystallized from the magma chamber should be fayalite. Either the zoning structure or the reaction rim structure of fayalite, plagioclase, aegirine reflects that the magma chamber is changing chemically and in the oxidation-reduction condition, and is in the unstable equilibrium state.

Rocks comprising the cone of Tianchi volcano belong to trachybasalt, trachyte and pantellerite zones as shown in fig. 2. The chemical composition of volcanic rocks erupted during either the cone-forming stage or the modern time can be summarized into two groups as trachybasalt with 49%—51.12% SiO_2 and trachyte and pantellerite with 65%—77.45% SiO_2. Their common feature is rich in K_2O and the lack of rocks with content of SiO_2 between 52% and 64%. These indicate that rocks of the Tianchi volcano cone come from two different magma source areas. Trachybasalt, similar to the basalt of shield-forming stage, should come from the magma eruption of mantle magma reservoir, while trachyte and pantellerite may come from the magma eruption of crustal magma chamber.

3 Materials of modern eruption of Tianchi volcano

Different from those materials erupted during the shield-forming stage and the cone-forming stage with lava eruption as their major ones, the modern time erupted materials of Tianchi volcano are mainly airfall deposits formed by explosive eruption and volcanic pyroclastic flow (ignimbrite) formed by the breakdown of volcano mouth. The deposits of multi-periods can be recognized in the profile along Tianwenfeng. These pumices are almost all of comenditic except for the black pumice formed by historical eruptions at the uppermost part of Tianwenfeng, which is of trachytic rocks. The pumice of earlier eruptions (>2 024 aB.P. or 4 105 aB.P.) is light yellow, light yellowish brown and grey with the content of H_2O^+ significantly higher than that of the pumice of other periods. The pumice erupted at 1 215 ± 15AD is mostly white or greyish white. Those pumices erupted historically are grey—grey black. All the pumices are of foamy shape, consisting practically of bubble holes and bubble walls of different thickness. These bubble walls are mostly glassy, but with anorthoclase, aegirine and a small amount of micro-fayalite phenocrystal. The SiO_2 of pumice is mostly between 70% and 74%, and is rich in K_2O but poor in CaO and MgO, very similar to trachyte or pantellerite of the cone-forming stage.

The Meteorological Station pantellerite consists of pantelleritic clastic rock, clastogenetic lava and obsidian. The phenocrysts of either pantellerite or bergmahogany are anothoclase, aegirine and individual fayalite similar to those seen in the pumice, with their elemental chemistry also the same as 70%—73% SiO_2, high K_2O and low CaO, MgO. It should be pointed out that either pantelleritic pumice or the Meteorological Station pantellerite is similar to alkaline granite in the major element composition and may be regarded as the erupted phase of alkaline granite.

4 Trace elements in the materials erupted during various stages at Tianchi volcano1)

4.1 Compatible elements

Cr, Ni, Co in the basaltic rocks erupted during the shield-forming stage, the Laohudong basaltic rock of cone-forming stage and the basaltic trachyandesite co-erupted with pantellerite magma of pantellerite are all significantly lower than those in the basalts in eastern China and other areas. It indicates that the basaltic magma erupted during various stages at Tianchi volcano is one kind of magma having undergone the differentiation crystallization evolution. The results of geophysical probing also indicate that there exist mantle magma chambers in the upper mantle beneath the area of Tianchi volcano. Meanwhile, the Cenozoic basalt of tens of thousands of square kilometers in Changbaishan area also requires that a mantle magma source area should be present[8].

4.2 Rare earth elements and other incompatible elements

The patterns for REE and incompatible elements of representative rocks in the three stages of Tianchi volcano are shown as figs. 3 and 4. We may first note that ΣREE, REE patterns (fig. 3) and La/Sm of basaltic rocks in Tianchi volcano area, erupted during either shield-forming stage, cone-forming stage or modern time, are all extremely similar. This implies that they have a common magma source area. ΣREE increases from basaltic rocks to trachyte of cone-forming stage and modern erupted materials with pantellerite as its majority. However, the REE patterns for these rocks remain rather similar (see fig. 3). Although the La/Sm ratio increases from that of basaltic rocks (3—4.5) to those of trachyte and pantellerite (5—7.5), the La/Yb ratios are still within the range 15—21, indicating there is a certain relationship between them. In the La/Sm-La graph suggested by Treuil et al. (1975), the trend of crystallization differentiation can also clearly be seen.

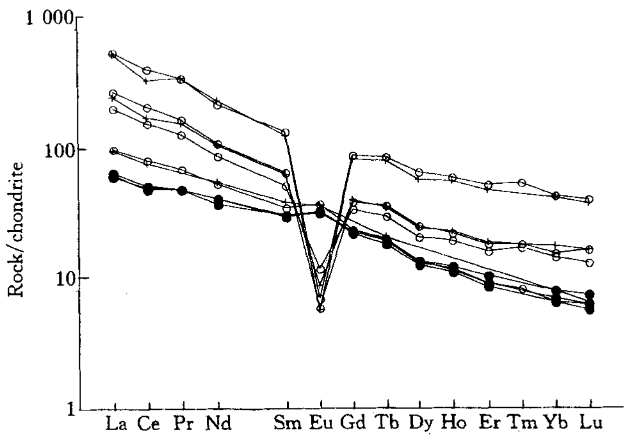

Fig. 3. Chondrite-normalized REE patterns of Changbaishan Tianchi volcano erupted material. ○, Modern historical eruptions; +, cone-forming period; ●, shield-forming period.

All the trachyte and pantellerite have strong negative Eu anomaly, while all the basaltic rocks have positive Eu anomaly to different extents (see fig. 3). The former reflects that the magma of trachyte and pantellerite has experienced differentiation crystallization of plagioclase. As mentioned above, this kind of differentiation crystallization of plagioclase can be demonstrated by the presence of corroded plagioclase phenocrystal (andesine-oligoclase) in trachyte

1) The data of 46 trace elements are provided by Zhang Ming and Liu Ruoxin, all obtained from ICP/MS.

or by the appearance of little inclusions of plagioclase (oligoclase) present in pantellerite as inclusion mineral. Tang Deping (1990) expounded the key role of differentiation crystallization of plagioclase for the formation of trachyte and pantellerite in the Tianchi volcano cone. The positive anomaly of Eu in basalts also reflects the partial crystallization of plagioclase (labradorite) in the mantle magma reservoir. These crystallized plagioclases have not descended along with olivine to the bottom of the magma chamber, but float in the basaltic magma and remain in Junjianshan basalt as phenocrystal or glomeroporphyric aggregate in the basaltic rocks, leading to the positive Eu anomaly.

From the Ba, K, Sr peaks in the incompatible element patterns of basaltic rocks in various stages shown in fig. 4 and the positive Eu anomaly shown in fig. 3, it can be interpreted that plagioclase crystals from differentiation crystallization remain in the basaltic magma, while it is contrary for trachyte and pantellerite erupted during the cone-forming stage and in the modern time. Ba and Sr negative anomaly shown in fig. 4, together with significant Eu negative anomaly shown in fig. 3, indisputably demonstrates the crucial role of differentiation crystallization of plagioclase in the formation of magma for trachyte and pantellerite in Tianchi volcano. The Ti and P negative anomaly may indicate that there is differentiation crystallization of pyroxene and ferrotitanium oxides as well. There appears significant anomaly between a trachyte (H-20) of the cone-forming stage and the pantellerite (BT-5) in incompatible trace elements. Significantly heading toward the upper crust composition region in the Th/Nb-Th and Nb/Pb-U/Pb graphs indicates that these rocks may have experienced the mixing of the crustal composition. The isotopic composition of BT-5 also indicates that there has been the participation of crustal composition.

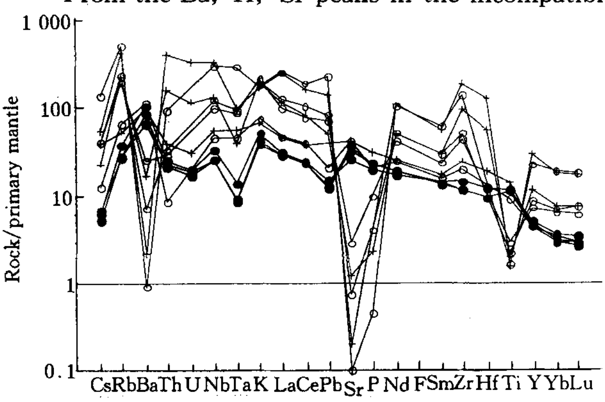

Fig. 4. Primary mantle-normalized patterns of incompatible elements for Changbaishan Tianchi volcano erupted material (legend as figure 3).

All the above-mentioned low Mg/(Mg + Fe) ratio of the major elements, the low Ni, Cr, Co contents of compatible elements of basalts and the characteristics of REE and other incompatible elements in various rocks at the Tianchi volcano may support the view that the evolution magma of the Tianchi volcano has experienced two differentiation crystallization processes in both the mantle magma reservoir and the crustal magma chamber.

5 Sr, Nd, Pb isotopic composition of volcanic rocks of various stages of Tianchi volcano

The research data on isotopic geochemistry of Tianchi volcanic rocks are still not much. After studying the Sr, Nd, Pb isotopic composition of rocks in Tianchi volcano area (3 samples of basaltic rocks——early Pleistocene to Pliocene; 3 samples of trachyte——mid-Pleistocene and 2 samples of trachyte and pantellerite of Holocene) Xie Guanghong et al. (1988) believed that these volcanic rocks of different petrogragh and periods are the magma system resulting from the evolution of magma from the same source, and attributed the addition of crustal materials to the source, as indicated by isotopic tracing, to the trace left by recycling of sediments brought in during the subduction of West Pacific Plate to the mantle system. Zhang Ming has newly provided 6 data on Sr-Nd isotopes of shield-forming basaltic rocks and 6 data on Sr-Nd isotopes of cone-forming trachyte, and by projecting the above-mentioned data onto the Sr-Nd isotope gragh it can be seen that either the shield-forming, cone-forming or modern erupted materials, except some individual ones deviating toward the EMII direction due to the mixing of crustal materials, all concentrate between DMM, EMI and EMII but closer to the value of EMI and primary mantle (fig. 5), and quite close to the Sr-Nd-Pb isotopic composition range of North China-Northeast China quasi-primary mantle region demarcated by Zhou et al. and Liu et al.[9,10]. This may be attributed to the location of this area, which is on the over 600 km deep mantle wedge at the frontier of West Pacific Plate subduction zone[11]. The frontier of the subduction zone with a depth up to 600 km may lead to local convection of the deep mantle composition, causing the Cenozoic volcanic rocks in the eastern part of Northeast China, including various rocks of Tianchi volcano, not only to have primary mantle composition (PM) from the deep mantle but also to be superimposed by the mantle composition enriched by metasomatism of the Sr-Nd-Pb isotopic composition points of various volcanic rocks distributed around the value of primary mantle but close to the EMI end. These also indicate that the Tianchi volcanic rocks, including trachyte and pantellerite, come from the same mantle source region. The high $^{87}Sr/^{86}Sr$ value of some individual trachytes (BT-5 and X-17) as well as the $^{87}Sr/^{86}Sr$ values of all the erupted materials of cone-forming stage and modern time being a little higher than those of the basaltic rocks of shield-forming stage may be explained by different degrees of crustal material mixing which they have suffered in the crustal magma chamber. The Sr isotope data of 10 samples provided in this paper and those provided by Xie et al. evidence that there is a growth and decline relationship between $^{87}Sr/^{86}Sr$ and $1/Sr$ in some samples (X-17, K-1, H-16 and Bt-5)[12], i.e. they have suffered the contamination of crustal composition. The $^{87}Sr/^{86}Sr$ of them, all larger than 0.705 3, indicate that trachyte and pantellerite come from crystal differentiation of mantle magma are both erupted from the crustal magma chamber. The result of geophysical sounding indicates that both the crustal magma chamber and the upper mantle magma reservoir exist under the Tianchi volcano, and that there existed the fact of co-eruption of basaltic trachyandesite and pantellerite magma during the early period of major eruption of the year 1 215 ± 15[8]. Therefore, the existence of the crustal and mantle double-layer magma chamber has been strongly supported by the result of geophysical probing and the fact of co-eruption of two kinds of magma. Based on the above data, we proposed the model of magma evolution of Chargbaishan Tianchi volcano (figure 6).

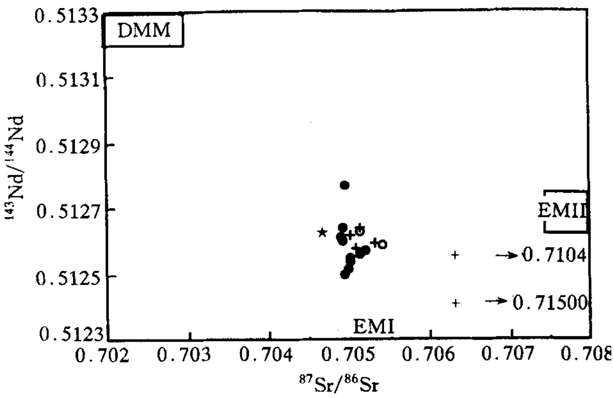

Fig. 5. The diagram of $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ for volcanic rocks from Changbaishan Tianchi volcano.

6 Conclusions

1) The Tianchi volcanic rocks consist of basaltic rocks-trachybasalt and basaltic

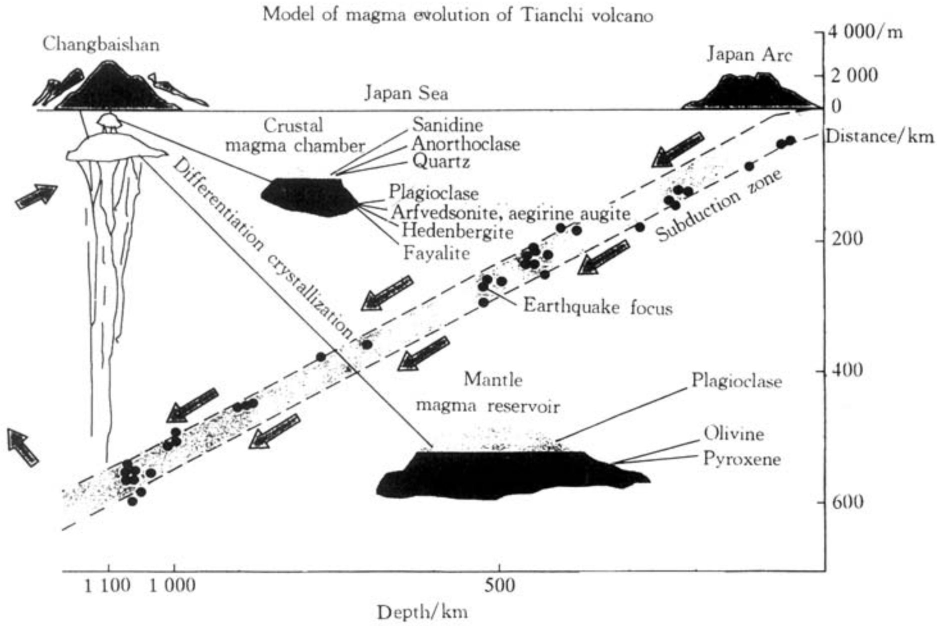

Fig. 6. The model of magma evolution of Changbaishan Tianchi volcano. The distribution of earthquake focus in the subduction zone is based on the data by Zhang (1983); the data for mantle and crustal magma chamber is provided by Liu et al. (1996).

trachyandesite, tholeiite and basaltic andesite of the shield-forming stage, trachyte and pantellerite of the cone-forming stage and modern eruption. The low Mg value and low Ni, Co, Cr contents and the incompatible element characteristics of the basaltic rocks indicate that this kind of basalt magma is the one which has experienced the crystal differentiation evolution of part of magnesium iron minerals and plagioclase. After the evolved magma of its alkalic series enters the crust, the crystallization differentiation of plagioclase, fayalite, hedenbergite-aegirine, etc. further takes place in the crustal magma chamber, leading to the formation of trachyte and pantellerite of the cone-forming stage and modern eruption. Therefore, the whole Tianchi volcanic rocks belong to the high potassium trachybasalt-basaltic trachyandesite-trachyte-pantellerite system, and Tianchi volcano is a multiple genesis combined volcano composed of typical bimodality of magma.

2)The basaltic rocks erupted during different stages have similar $\sum$REE, REE pattern, positive Eu anomaly and La/Sm ratio as well as extremely similar incompatible element pattern, indicating that they have the same magma source region, while basaltic rocks, trachyte and pantellerite also have a similar REE distribution pattern (except strong negative Eu anomaly) and La/Yb ratio as well as extremely similar Sr-Nd-Pb isotopic composition, indicating that they have not only the common magma genesis but also the close evolution relationship, in which the differentiation crystallization plays a key role.

3) The Tianchi volcano erupted materials at the cone-forming stage and modern time mainly come from the crustal magma chamber but sometimes are accompanied by basalt magma from the mantle, even it is believed that the major eruption of the year 1 215 ± 15 may be triggered by the injection of mantle magma into the crustal magma chamber[8], leading to the fact that co-eruption of basaltic trachyandesite magma and pantellerite magma appeared at the early period of this major

eruption. This shows that the crustal magma chamber and mantle magma reservoir beneath the Tianchi volcano are a unified magma system. This point is important for the understanding of magma evolution and eruption mechanism of Tianchi volcano.

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