Petrogenesis of the Cenozoic Volcanic Rocks from the Northern Part of Qinghai-Xizang (Tibet) Plateau *

LAI SHAOCONG (赖绍聪)
(*Department of Geology, Northwest University, Xi'an* 710069, *China*)

Abstract: Based on electron probe analyses of the minerals and bulk composition of the Cenozoic volcanic rocks from Yumen and Hoh Xil lithodistricts, Qinghai-Xizang plateau, the forming conditions including the temperature and pressure of those rocks are studied in this paper. According to the thermodynamic calculation results of mineral-melt equilibrium, the depth of the asthenosphere superface (about 75 - 130 km) for the northern part of the Qinghai-Xizang plateau during the Cenozoic is suggested. Finally, this paper indicates that the Cenozoic volcanic rocks in the northern part of the Qinghai-Xizang plateau mainly consist of shoshonite series. Their forming temperature is 630 - 1039 ℃ and forming pressure is between 2.3 - 4.0 GPa. The rocks were formed in the intracontinental orogenic belt, of which the primary magma was originated from a particular enrichment upper mantle and accreted crust-mantle belt or directly from asthenospheric superface as a result of partial melting of pyrolite.

Key words: Qinghai-Xizang plateau; Cenozoic; volcanic rock; petrogenesis

Introduction

For a long time, the Qinghai-Xizang plateau has been considered as the result of collision between the India and Eurasia continents. It has aroused great attention of geoscientists both at home and abroad and is regarded as the most important example of the collision-orogenic belt in the world. As the theory of plate tectonics has been put forward, the Qinghai-Xizang plateau is further regarded as a typical ideal region for scientists to study the geological evolution of an orogenic belt, to set up the development model of continental lithosphere and to solve the tectonic problems in Asia, even throughout the world. The Cenozoic volcanic rocks in the northern part of the Qinghai-Xizang plateau were formed in the intracontinental orogenic belt, of which the primary magma was originated from a particular enrichment upper mantle and accreted crust-mantle belt or directly from asthenospheric superface as a result of partial melting of pyrolite. From detailed studies of the Cenozoic volcanic rocks, the effective petrological constraints on the geological processes at depth can be developed. And, of course, it is also a "window" on the orogeny/uplift mechanism of the Qinghai-Xizang plateau. However, the Cenozoic volcanic rocks distributed in the northern part of the plateau have not yet been well documented. Especially, detailed research on the rock forming temperature and pressure, the origination depth of the primary magma system and the depth of the asthenospheric superface in the northern part of the Qinghai-Xizang plateau during the Cenozoic are still scarcely known. In this paper, the petrological and physicochemical methods such as mineral thermometry and thermodynamics calculation of mineral-melt equilibrium are used to discuss the formation process of the Cenozoic volcanic rocks, and the

ISSN 1000-9426

* The project was supported by the National Natural Science Foundation of China (No. 49234080), the Geological Sectional Foundation of MGMR (No. 8506201, 8506207) and the Science Foundation of Northwest University (97NW23).

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

evolutionary model, uplift dynamic mechanism and burial depth of the asthenospheric superface for the Qinghai-Xizang plateau.

Regional Geology

The Qinghai-Xizang plateau is one of the regions in China where Cenozoic volcanism was very active. In the northern part of the plateau are widespread Cenozoic volcanic rocks which form a series of lithozones and lithodistricts on a grand scale. The volcanic rocks extend to western Kunlun Mountain and Qilian Mountain in the north, to the Himalaya-Gangdise region in the south, to the Hengduanshan Mountain, Qinling in the east and to Kala Kunlun in the west (Pan Guitang et al., 1990).

The Yumen Cenozoic volcanic lithodistrict is located at the juncture between the NWW-trending Qilian Mountain and the NEE-trending Altun Mountain, which belongs to the north margin of the Qinghai-Xizang plateau (Pan Guitang et al., 1990). This lithodistrict consists mainly of the Hongliuxia and Hanxia Late Cenozoic volcanic rock bodies. Our samples were collected from the Hongliuxia rock neck and rock flowage. The Hongliuxia Pleistocene volcano-neck is located 40 km northwest of Yumen City, consisting of tephrite and trachybasalt. And it is surrounded by Cretaceous-Tertiary black-grey shales interbedded with grey argillaceous sandstone. The boundary line between the volcano-neck and the country rock is well defined and the contact plane is almost erect. The drag structure and wrinkle have been identified in the country rocks, which were due to the upwelling of the magma. About 100 meters south of the volcano-neck is a basaltic flowage which overlies the Cretaceous-Tertiary shale and argillaceous sandstone. The flowage extends in the NE-SW direction. It is about 100 meters long, 30 meters wide and 7 meters thick. The Hanxia Cenozoic volcanic lithodistrict is located 15 km west of Yumen City, which is a river valley extending into the northern piedmout of the Qilian Mountain and cutting through the Cretaceous-Tertiary stratigraphic sequence. The Cenozoic volcanic rock distributed in the Hanxia River Valley is a lava flowage which is NWW-trending as a long lava dome.

The Hoh Xil Cenozoic volcanic lithodistrict is located in the northern part of the Qinghai-Xizang plateau. The intense intracontinental Cenozoic volcanism in this region resulted in a number of lava sheets and subvolcanic rock bodies of different sizes which now occur as lava platforms with an elevation of about 5000 m (Sun Yangui, 1992). Affected by the preexisting NWW-trending structure zones, there were formed several NWW-trending volcano-active zones in the area during the Cenozoic when the magma overflowed and/or intruded nearly to the ground surface. And the Hoh Xil north-margin volcanic rock zone is the northernmost one. It was developed between Hoh Xil and the Bokaleiketage Mountain. Along the East Kunlun, this volcanic rock zone extends from the Damao Mountain in the east through the Lexiewudan Lake to Xinjiang Autonomous Region. It is about 200 km long in Qinghai Province and the volcanic rocks are mainly Miocene in age (14 - 24 Ma) (Sun Yangui, 1992).

The Series and Association of the Cenozoic Volcanic Rocks

The Cenozoic volcanic rocks developed in the northern part of the Qinghai-Xizang plateau are mainly a series of intracontinental shoshonite-latite-trachyte-rhyolite (Lai Shaocong, 1996). They are rich in potassium. Almost all of the rocks are high in total alkali ($K_2O + Na_2O > 5\ \%$) and high in K_2O/Na_2O (> 0.6 at $50\ \%\ SiO_2$, > 1.0 at $55\ \%\ SiO_2$). They have high, but variable Al_2O_3 (mostly between 12 % - 18 %). Their petrological and geochemical characteristics are very

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

similar to those of shoshonite assemblages developed in island arc-continental marginal arc regions in the world (Lai Shaocong, 1996). However, this group of Cenozoic volcanic rocks distributed in the Qinghai-Xizang plateau was formed after the collision between the India and Asia plates. So, we call them the intracontinental orogenic shoshonite series. Compared with the island arc-continental marginal arc shoshonite assemblage, the intracontinental orogenic shoshonite in the Qinghai-Xizang plateau has higher contents of TiO_2 (1.30 %), Zr (320×10^{-6}) and Nb (37×10^{-6}) than those of the island arc-continental marginal arc shoshonite assemblage (TiO_2 = 0.95 %, Zr = 150×10^{-6}, Nb = (5 - 7) $\times 10^{-6}$, but lower than those of continental rift valley alkali basalts (TiO_2 = 2.20 %, Zr = 800×10^{-6}, Nb = 50×10^{-6} - 90×10^{-6}) (Condie, 1982). It is implied that the intracontinental orogenic shoshonite series in the Qinghai-Xizang plateau exhibits not only the geochemical characteristics of island arc volcanic rocks, but also those of within-plate volcanic rocks. This is in consistence with the dual nature of intracontinental tectonics setting for the Qinghai-Xizang plateau (not only belonging to the orogenic belt, but also to the within-plate setting) (Deng Jinfu et al., 1996a).

Forming Temperature of the Volcanic Rocks and Magma

According to the electron microprobe analyses (Lai Shaocong, 1996) and the two-feldspar thermometry data (Stormer, 1975), the forming temperature of the volcanic rocks is obtained as listed in Table 1. Actually, the two-feldspar thermometer is based on the fact that the partitioning coefficient of the Ab component between plagioclase and potassium feldspar is a fixed value, which is in close relation with the forming temperature of the volcanic rocks. Therefore, the temperature values listed in Table 1 should mainly represent the forming temperatures of the rocks, which should be lower than the temperature value of source region of the magma system.

The paragenetic minerals Opx and Cpx have been identified in the sanidine megacryst-bearing trachyte collected from the Hoh Xil lithodistrict. And their crystal chemistry molecular formulas are listed below:

Opx: $(Mg_{0.764}\ Ca_{0.04}\ Na_{0.025}\ Fe^{2+}_{0.167}\ Mn_{0.004})^{M_2}_{1.00}\ (Mg_{0.734}\ Al_{0.085}\ Cr_{0.013}\ Fe_{0.16}\ Ti_{0.004})^{M_1}_{0.996}\ (Si_{1.889}Al_{0.088})_{1.977}O_6$

Cpx: $(Ca_{0.794}\ Mg_{0.124}\ Fe_{0.04}\ Mn_{0.002}\ Na_{0.039})^{M_2}_{0.999}\ (Mg_{0.66}\ Fe_{0.211}\ Al_{0.075}\ Cr_{0.007}\ Ti_{0.048})^{M_1}_{1.001}\ (Si_{1.845}Al_{0.075})_{1.92}O_6$

Based on this, the forming temperature of the trachyte should be 1039.73 ℃ (1312.73 K) as determined by a two-pyroxene thermometer (Wood et al., 1973). This temperature value represents the eutectic temperature at which the clinopyroxene and orthopyroxene made up the equilibrium paragenetic pair. In fact, the pyroxene is the mineral that crystallized early from the trachytic magma system. That is to say, this temperature value (1039.73 ℃) should be higher than the forming temperature of the trachyte but slightly lower or close to that of the source region of the magma system.

According to the electron microprobe analyses of volcanic glass (Table 2) and plagioclase phenocryst (An = 38.9, Ab = 53.3, Or = 7.8; Lai Shaocong, 1996) in the dacite-liparite collected from the Hongshuihe lava dome in the Hoh Xil lithodistrict, the quenching temperature of the volcanic glass was 901.5 ℃ (1174.5 K) as determined by plagioclase geological thermometry (Kudo et al., 1970). It is obvious that this temperature value is much closer to the forming temperature of the rock. And it is in consistence with the temperature values (633 - 991 ℃) listed in Table 2 as determined by two-feldspar thermometry.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Table 1. Results of two-feldspar thermometric measurement of the Cenozoic volcanic rocks from the Yumen and Hoh Xil lithodistricts

Lithodistrict	Rock	Ab molecule (%)		T (°C)	Remark
		Plagioclase	K-feldspar		
Yumen	Trachybasalt	84.6	42.2	659.8	Phenocryst
Hoh Xil	Trachyandesite	62.1	33.0	784.8	Or phenocryst and Pl reaction rim
		48.1	33.0	991.5	Phenocryst
	Trachyandesite	80.0	32.4	633.0	
Mangkang	Trachydacite	72.8	30.8	666.8	Phenocryst
	Trachyte	65.1	37.2	792.6	

Table 2. Chemical composition of the volcanic glass

Oxide	Mass (%)	Molecule number	Atomic number	Mol fraction (X)
SiO_2	65.66	1092.8	1092.8	$X_{Si} = 0.740$
Al_2O_3	14.46	141.7	283.4	$X_{Al} = 0.192$
CaO	3.07	54.8	54.8	$X_{Ca} = 0.037$
Na_2O	1.40	22.6	45.2	$X_{Na} = 0.031$
Total			1476.2	1.000

Analyzed at the Electron Microprobe Section of China University of Geosciences (Beijing) (1993).

The Forming Conditions of Sanidine Megacrysts

Trachyandesite collected from Hoh Xil contains a sanidine megacryst measuring about 5 ×2 (cm) in grain size and occurring as a perfect short columnar euhedral crystal. The megacryst is optically homogeneous and only a few fine-grained plagioclase grains have been identified in the outer part of the metacryst. X-ray diffraction analysis indicates that the absolute value of the Ragland coefficient (δ) for the megacryst is 0.86 and its monoclinic ordering degree (Sm) is 0.068. Both the coefficients indicate that the megacryst belongs to high temperature sanidine. In fact, the intrinsic quality of ordering degree for feldspar is the aluminum's occupation probability in the feldspar lattice. Using the method suggested by Kamencev and Cmetannikova (1977), we calculated the aluminum's occupation probability of the sanidine megacryst. The result indicates that the aluminum's occupation probabilities at the lattice positions of T_{1o}, T_{1m}, T_{2o}, T_{2m} are 0.33989, 0.22613, 0.21699 and 0.21699. And the Thompson coefficients of the megacryst Y (0.11) and Z(0.13) are small, which means the megacryst is low in ordering degree, belonging to high temperature sanidine.

Based on the three-peak method, the structure coefficient η was put forward by Zeuisaki (1972). It is in close relation with $2\theta_{060}$ and $2\theta_{204}$:

$$\eta = 6.68 \times 2\theta_{060} - 7.44 \times 2\theta_{204} + 99.182$$

where η is the mark of ordering degree for alkali feldspar and $Sm \approx 1.6\eta$. As we know, the η coefficient is related to the forming temperature of the alkali feldspar. According to the diagram of η versus temperature (Zeuisaki, 1972), it is determined that the forming temperature of the sanidine megacryst in the Cenozoic trachyandesite collected from the Hol Xil lithodistrict was about 840 °C. However, this value only represents the lowest temperature at which the feldspar maintains the lattice structure state. That is to say, the crystallizing temperature of the feldspar was higher and the present lattice structure of the megacryst is a metastable phase. So, the value of 840 °C tested by the η coefficient should be the lowest limit of crystallizing temperature for the sanidine megacryst in the trachyandesite from the Hoh Xil lithodistrict. And their initial-stage crystallizing temperature should be much higher.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

According to the chemical composition of the sanidine megacryst and its plagioclase fine-grained inclusions, using two-feldspar thermometry, we determined that their forming temperature was 842.8 ℃ (Table 3), which is approximate to the temperature value tested by the η coefficient.

Table 3. Results of two-feldspar thermometric measurement for the sanidine megacryst from the Hoh Xil lithodistrict

Rock	Ab molecule (%)		T (℃)
	Plagioclase	K-feldspar	
Trachyandesite	70.00	27.70	842.8

Table 4. The An molecular percentage of the sanidine megacryst and normal alkali feldspar phenocryst from the Hoh Xil lithodistrict

No.	Location	Rock type	An molecule (%)	Remark
2SB6	Hoh Xil	Trachyandesite	0.9	Phenocryst
2SB1	Hoh Xil	Trachyandesite	0.6	Phenocryst
2SB1	Hoh Xil	Trachyandesite	0.2	Megacryst
2SB1	Hoh Xil	Trachyandesite	0.2	Megacryst

Analyzed by the Electron Microprobe Section of China University of Geosciences (Beijing) (1993).

The An component in the feldspar is unstable at high pressure. Its incongruent melting will occur at high temperature and 1.0 GPa pressure, forming corundum + melt. However, albite and sanidine are stable at high pressure. The sanidine megacryst in trachyandesite from the Hoh Xil lithodistrict is obviously optically homogeneous. No zonal texture and twin crystal have been recognized. The X-ray diffractometric result indicates that there is no exsolution texture in the megacryst. Especially, the chemical composition of the megacryst is homogeneous from the outer part to the inner part. This implies that the megacryst was the result of perfect crystallization of the magma system at high pressure and temperature. The chemical composition analysis (Table 4) indicates that the An molecular percentage of the sanidine megacryst is higher than that of normal alkali feldspar phenocryst from the Hoh Xil lithodistrict. That means the crystallization depth and pressure of the megacryst should be higher than those of the normal alkali feldspar phenocryst.

On the Q-Or-Ab diagram (Fig. 1a), the trachyandesite collected from the Hoh Xil lithodistrict falls on the right side of the fractional crystallization line qm (thermal valley) and below the syncrystallization line WS (point P). On the An-Ab-Or diagram (Fig. 1b), the point is located on the two-feldspar plane (HGEF) where the first crystallization area of plagioclase is located. That means the plagioclase would crystallize first from the magma system of the trachyandesite at low pressure (0.2 GPa). If the temperature decreases slowly, the crystallized mineral will react with the residual melt to adjust its own composition. With further decreasing temperature, the plagioclase will crystallize continuously and the melt varies in composition along line PB. At point A, the melt composition reaches the two-feldspar plane. At this time, plagioclase and K-feldspar will crystallize together. To point B, the melt composition reaches the quartz-feldspar plane (WXGS), then varies along syncrystallization line GH. At this time, quartz and feldspar will crystallize together. Finally, the melt composition reaches the lowest point (H) of the line, and the crystallization is finished. Therefore, the crystallization sequence of the trachyandesite from the Hoh Xil lithodistrict at shallow levels of the magma chamber should be: plagioclase → potassium feldspar → quartz.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

It is obvious that the potassium feldspar megacryst cannot be formed at low pressure in this trachyandesitic magma system. On the contrary, the plagioclase has a longer crystallization route and a better crystallization environment. What was first crystallized should be plagioclase rather than potassium feldspar. Therefore, the sanidine megacryst in the trachyandesite collected from the Hoh Xil lithodistrict cannot be formed at lower pressure. In fact, the pressure (P_{H_2O}) has an important influence on the crystallization of the Q-Ab-Or system. With increasing P_{H_2O}, the syn-crystallization line WS would shift downward the Ab-Or boundary. Undoubtedly, the pressure is a very important factor affecting the formation of the sanidine megacryst. The increasing of pressure should be favorable to the first crystallization of potassium feldspar from the magma system to form megacryst. In addition, the overcooling degree, cooling rate, nucleus formation rate, crystallization rate and viscosity coefficient of the melt can also influence the formation process of the megacryst.

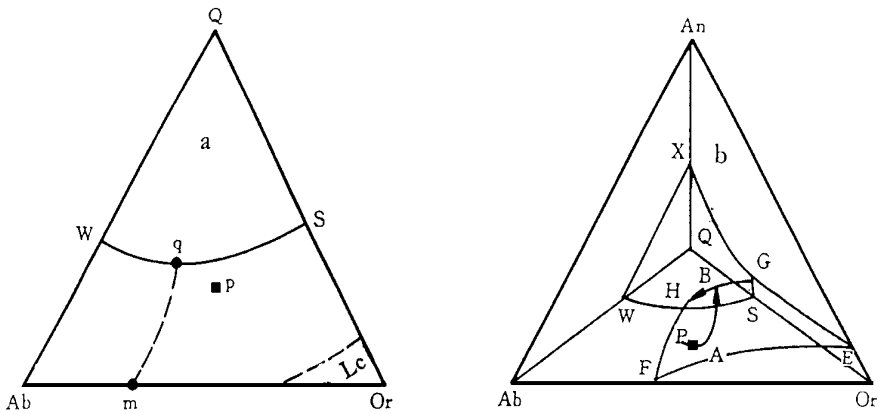

Fig. 1. Projection of normative minerals in Ab-Or-Q diagram (a) and An-Ab-Or-Q diagram (b) for trachyandesite from the Hoh Xil lithodistrict (after Carmtchael, 1963).

Another matter of dispution is whether the megacryst is the result of crystallization of its host magma system or belongs to xenocrysts. Some scientists consider it as a xenocryst or a crystal shard coming from mantle or crust because it is often intergrown with pyrolite enclaves, and cataclastic texture and sharp-edged shape have been identified in the megacryst. Microscopic study shows that mineral kink band, plastic deformation, undulatory extinction and aggregate (plastic deformation core-mantle structure) were not found in the sanidine megacryst from the Hoh Xil trachyandesite. Moreover, the sanidine megacryst in the area studied possesses magmatic-type high-temperature and low-degree lattice structure, exhibits euhedral crystal texture and occurs as typical single crystal. Its composition is in consistence with that of the host trachyandesite. Therefore, the sanidine megacryst in this region should be the result of crystallization from the potassium alkaline magma system at deep chamber. When the magma was originated from the lower crust or upper mantle, sanidine megacryst began to form progressively. Then as the megacryst upwelling with the magma, its crystallization slowed down. The emergence of fine-grained plagioclase in the magma system implies that the megacryst's crystallization nearly finished. At this stage, it is possible that the sanidine megacryst (especially its outer part) contains some fine-grained plagioclase crystals. If so, the temperature value listed in Table 3 (842.8 °C) may represent the temperature conditions of sanidine megacryst crystallization at the final stage and normal plagioclase crystallization at the initial stage. It should be consistent with the value (840 °C) deduced from the η coefficient which represents the lowest temperature limit for the

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

sanidine megacryst to maintain its lattice structure, but lower than the temperature at which the megacryst began crystallizing.

Estimation of Generating Pressure of the Magma System

As everybody knows, it is difficult to estimate the magma-generating pressure and depth. On the basis of experimental petrology at high pressure and temperature (Ghiorso et al., 1980) and mineral-melt equilibrium thermodynamics (Carmichael et al., 1974), the a_{SiO_2} decreases with increasing magma-generating pressure (depth) and increases with increasing SiO_2 content in the rocks (Fig. 2). Detailed studies, according to this regular pattern, have revealed that for the Cenozoic volcanic rocks in the Qinghai-Xizang plateau their primary and/or approximately primary basaltic magma originated from the upper mantle-lower crust depth from 85.1 - 108.9 km (Table 5; Lai Shaocong, 1996).

Table 5. Depth and pressure of the magma source region for the Cenozoic volcanic rocks in the Qinghai-Xizang plateau

Location	Rock	SiO_2(%)	Mg'	P(GPa)	Depth (km)
Western Kunlun	Tephrite	43.17	0.62	2.58	85.1
Dahongliutan	Tephrite	44.89	0.65	2.25	74.3
Lixian	Mafurite	38.65	0.65	3.30	108.9

But the pressure listed in Table 5 should be slightly lower than the actual pressure in the primary magma source region. That is because of the influence of magma evolution which would cause the SiO_2 content to increase in the rock.

Based on the mineral-silicate melt equilibrium thermodynamics, we can estimate the equilibrium pressure and temperature between the upper mantle pyrolite and the magma system using the component activity (a_1) of basalt, which may represent the source region temperature and pressure conditions of the magma system. Generally, in almost all basaltic magmas, olivine is the early product of crystallization. Experimental study of a simple system shows that Fo-Fa belongs to perfect solid solution. Compared with the melt, olivine is rich in magnesium but poor in iron. Therefore, olivine-melt equilibrium can be used to estimate the liquidus pressure and temperature of the basaltic magma system. According to the buffering reactions:

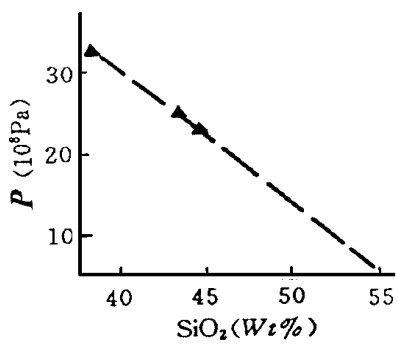

Fig. 2. Relation between magma forming depth and SiO_2(%) content (after Deng Jinfu et al., 1996b).

$$Fe_2SiO_4(liq.) \rightleftharpoons Fe_2SiO_4(Fa)$$

$$Mg_2SiO_4(liq.) \rightleftharpoons Mg_2SiO_4(Fo)$$

This paper calculated the olivine-melt equilibrium temperature and pressure of the Cenozoic alkali basalt collected from the Yumen lithodistrict (Table 6). The *P* and *T* values may represent the liquidus pressure and temperature of this alkali basaltic magma system, and they would be close to the *P* and *T* conditions of the alkali basaltic magma's source region. The calculated result shows that the olivine-melt equilibrium pressure is 3.72 GPa, corresponding to an alkali basaltic magma-generating depth of about 120 km.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Table 6. Thermodynamic calculation of the olivine-melt equilibrium for Cenozoic tephrite from the Yumen lithodistrict

Quenching temperature	Theoretical composition of mineral at liquidus line		Component activity (10^{-4}GPa)		Φ value		Equilibrium condition	
	X^{Ol}_{FeO}	X^{Ol}_{MgO}	$a^{liq.}_{Fe_2SiO_4}$	$a^{liq.}_{Mg_2SiO_4}$	$\Phi_{Fe_2SiO_4}$	$\Phi_{Mg_2SiO_4}$	T(K)	P(GPa)
1263.5 (K)	0.066	0.934	2.123×10^{-2}	8.587×10^{-2}	87.288	566.58	1430	3.72

The calculation method from Deng Jinfu (1983) ①.

Detailed studies have revealed that the lga_{SiO_2} for the primary magma of leucotephrite is between 0.7 - 1.4 at 1100 ℃±(Carmichael et al., 1974). For the leucotephrite and fergusite samples collected from northern Xizang and northern Hoh Xil, it is supposed that their lga_{SiO_2} is about 1.0 (mean value between 0.7 - 1.4) and T = 1100 ℃ (obtained by two-pyroxene thermometry). In this case, their magma-generating pressure should be 4.0 GPa, corresponding to a magma-generating depth of about 130 km.

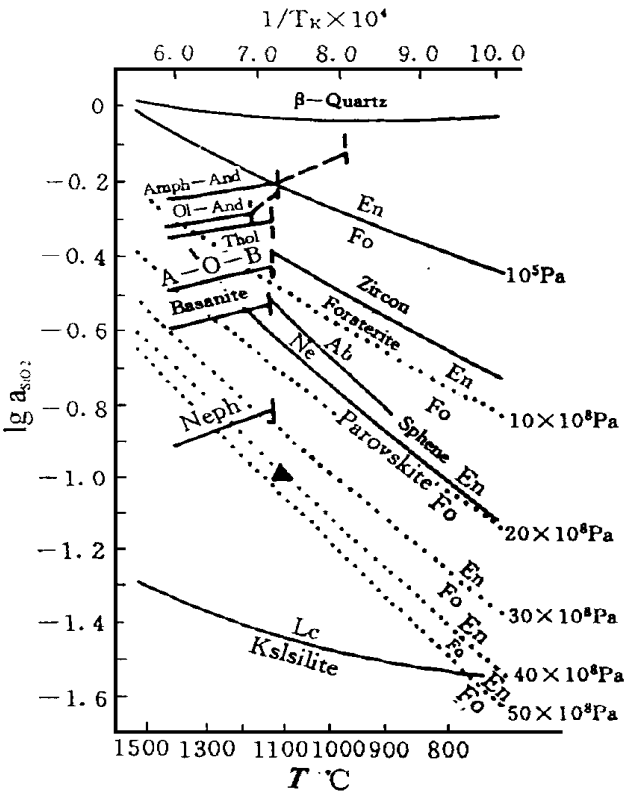

Fig. 3. Predicted temperature and pressure variations with the lga_{SiO_2} in typical lavas of various compositions (after Ghiorso et al., 1980).

It is important that basalt samples which possess the characteristics of primary magma and/or low evolution-degree magma should be chosen to estimate the basaltic magma-generating pressure and temperature. In fact, the primary magma originated directly from partial melting of the source rocks. The magma did not change in chemical composition when it rose from the deep part to the Earth's surface. The value of Mg'(Mg/Mg + Fe^{2+}) is one of the important markers to identify the primary magma type. Generally, the Mg' values for the primary magma type should be 0.68 - 0.75 (Frey, 1978) or 0.65 - 0.75 (Deng Jinfu, 1983) ①. The basalt samples used in this paper for pressure estimation give Mg' values of 0.62 - 0.68 (Lai Shaocong et al., 1996). They are basically consistent with the characteristics of primary magma or low evolution-degree magma type. Therefore, the calculated pressure and depth values in this paper can mainly represent the P and T conditions of the primary magma-generation in the region studied.

Buried-Depth of the Asthenosphere Superface and Petrogenesis

The bottom boundaries of the lithosphere estimated by different methods are different from

①Deng Jinfu, 1983, Mineral-melt equilibrium thermodynamics.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

one another because of different conceptions of the asthenosphere. Ringwood (1975) and Condie (1982) defined the asthenosphere as a weak layer which is easily subject to creep deformation and extends downward to about 700 km. It can be divided into two layers. The upper layer is equivalent to the low-velocity layer defined by seismic wave. The low-velocity layer is characterized by low seismic wave velocity, low Q value and high electrical conductivity. Condie (1982) indicated that only initial melting could be used to explain perfectly the three main characteristics of the low-velocity layer. Furthermore, the mutation boundary and high surface thermal current of the low-velocity layer are both consistent with the initial melting theory. Basaltic magma originated from the upper mantle by partial melting of pyrolite. Therefore, the generating-depth of primary basaltic magma can be used as a petrological constraint on the depth of the asthenosphere superface. And the asthenosphere conception defined petrologically is in agreement with the upper layer of the asthenosphere defined in terms of seismic wave. It is obvious that the petrological method in combination with the geophysics model would be much helpful to determine the bottom of the lithosphere.

The Cenozoic volcanic rocks were developed mainly along the northern and eastern parts of the Qinghai-Xizang plateau. Most of them did not contain enclaves of upper mantle peridotite and belong to the evolutionary magma system. Therefore, in this paper basaltic samples with high value of Mg' and low content of SiO_2 have been selected to calculate the depth of the asthenosphere superface. The calculated results indicate that the depth of the asthenosphere in the northern part of the Qinghai-Xizang plateau during the Cenozoic is about 75 - 130 km. And the depths obtained by geophysics methods are 104 km (Song Zhonghe et al., 1986), 90 - 130 km (Zhou Bin et al., 1991; An Changqiang et al., 1993) and 67 - 74 km (Zhuang Zhen et al., 1992). That is to say, the buried-depth of the asthenosphere obtained by the petrological method in this paper and that by the geophysics method are roughly in agreement with each other.

The isotopic characteristics (Xie Guanghong et al., 1992) indicate that the Cenozoic volcanic rocks in the Qinghai-Xizang plateau originated mainly from a particularly fertile upper mantle and an accreted crust-mantle mixed zone. Most of the volcanic rocks are high in $^{87}Sr/^{86}Sr$, low in $^{143}Nd/^{144}Nd$ and high in Pb isotopic composition. Their $^{87}Sr/^{86}Sr$ values are between 0.705 - 0.708, higher than those of the primitive mantle (0.7044), indicating that there could exist a lot of crustal material in the magma source region, which found its way into the upper mantle by crust/mantle recycling during the magma-generating process. The northern part of the Qinghai-Xizang plateau, in fact, was a typical collision tectonic setting in the Cenozoic era. It is possible for a lot of crustal material to enter the upper mantle because of the intense compression and contraction as well as thickening of the crust. So a particular accreted crust-mantle mixed zone was formed. Magma originated from this particular fertile accreted crust-mantle mixed zone must show obvious geochemical features of the island arc-type volcanic rocks. And the enriched component can be considered as a result of mantle metasomatism and/or mantle metamorphic process. On the other hand, it may be due to the entry of crustal material and its detaining at deep part by the subducted plate (ancient oceanic crust). In this case the isotope geochemical features indicate that the upper mantle in the northern part of the Qinghai-Xizang plateau should be enriched in incompatible elements and belongs to the inhomogeneous fertile mantle type.

In northern Qinghai-Xizang plateau are developed Cenozoic volcanic rocks which form a series of lithozones and lithodistricts extending more than 1000 km. They are composed mainly of shochonite originating from a bottom layer of the thickened crust and accreted crust-mantle belt or directly originating from the asthenosphere superface by partial melting of pyrolite. This kind of intracontinental orogenic shoshonite was due to the obstruction of the lithosphere-root beside the

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Qinghai-Xizang continental block. Because of the obstruction from the Tarim Craton lithosphere-root, the asthenosphere would slightly dome up and its material would upwell at the boundary between the Qinghai-Xizang plateau and Tarim, which would cause the formation of mantle-derived magma and its underplating at the Moho. On the other hand, the shortening and thickening of the crust for the Qinghai-Xizang plateau was favorable to the closing of the magma chamber which was underplating to the bottom of the crust. Thus, the underplating magma would have enough chance to interact with the crustal material, including partial melting of the crustal rock sequence, mixing between the mantle-derived magma and the crust-derived magma, and the fractional crystallization of magma systems. Conclusively, the formation of the Cenozoic volcanic rocks in the northern part of the Qinghai-Xizang plateau should be ascribed to this kind of typical tectonic setting (Fig. 4).

Conclusions

The Cenozoic volcanic rocks distributed in the northern part of the Qinghai-Xizang plateau are mainly of intracontinental orogenic belt shoshonite series. They originated from a bottom layer of the thickened crust or an accreted crust-mantle belt or directly originated from the asthenosphere superface by partial melting of pyrolite. Their formation was in close relation with the obstruction of the Tarim Craton lithosphere-root and the northward compression of the Qinghai-Xizang plateau as well as the shortening + thickening of the Qinghai-Xizang crust. The forming temperature of the Cenozoic volcanic rocks collected from the Hoh Xil and Yumen lithodistricts is within the range of about 630 - 1039 ℃, and their forming pressure between 2.3 - 4.0 GPa. Based on the thermodynamic calculations, the depth of the asthenosphere superface in the northern part of the Qinghai-Xizang plateau during the Cenozoic should be about 75 - 130 km. This conclusion is of significance and helpful for scientists to discuss in detail the uplift mechanism of the Qinghai-Xizang plateau and the dynamic processes at depth in intracontinental orogenic belts in the world.

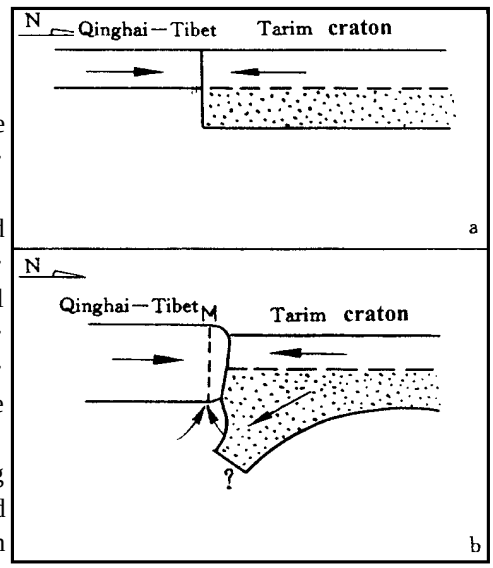

Fig. 4. Sketch formation model of Cenozoic volcanic rocks at the northern margin of the Qinghai-Xizang plateau. a. Northward obstruction of the Tarim Craton-northward movement of the Xizang plate; b. crust shortening and thickening of the Qinghai-Xizang plateau and the formation of Cenozoic volcanic rocks at the northern margin.

References

An Changqiang, Song Zhonghe, Chen Guoying, Chen Lihua, Zhuang Zhen, Fu Zhuwu, Lu Zhiling, and Hu Jiafu, 1993, 3-D shear velocity structure in North-West China: Acta Geophysica Sinica, v. 36, n. 3, p. 317 - 325 (in Chinese with English abstract).

Carmichael, I. S. E., F.J. Turner, and J. Verhoogen, 1974, Igneous petrology: New York, McGraw-Hill, p. 40 - 46.

Carmichael, I. S. E., 1963, The crystallization of feldspar in volcanic acid liquids: J. Geol. Soc., v. 119, p. 95 - 113.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Condie, K. C., 1982, Plate tectonic and crustal evolution: New York, Pergamon Press, p. 110 - 310.

Deng Jinfu, Zhao Hailing, Mo Xuanxue, Wu Zongxu, and Luo Zhaohua, 1996a, Continental roots-plume tectonics of China - key to the continental dynamics: Beijing, Geological Publishing House, p. 17 - 20 (in Chinese).

Deng Jinfu, Zhao Hailing, Luo Zhaohua, Lao Shaocong, and Li Yuwen, 1996b, Asthenosphere geochemistry and mantle fluids deduced from basaltic volcanic rocks, in Du Letian, ed., Geochemistry of mantle fluids and asthenosphere (asthenoliths): Beijing, Geological Publishing House, p. 58 - 96 (in Chinese with English abstract).

Frey, F. A., 1978, Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilities from south eastern Australia utilizing geochemical and experimental petrological data: J. Petrol., v. 119, p. 463 - 513.

Ghiorso, M. S. and I. S. E. Carmichael, 1980, A regular solution model for melt-aluminous silicate liquids: application to geothermometry, immiscibility, and the source regions of basic magmas: Contrib. Mineral. Petrol., v. 71, p. 323 - 342.

Kamencev, E. Y. and O. G. Cmetannikova, 1977, The composition and order degree testing for feldspar using powder method: Mineralogical Magazine of the Soviet Union, v. 106, p. 476 - 481 (in Russian with English abstract).

Kudo, A. M. and D. F. Weill, 1970, An igneous plagioclase thermometer: Contrib. Mineral. Petrol., v. 25, n. 1, p. 52 - 65.

Lai Shaocong, 1996, Cenozoic volcanism and tectonic evolution in the northern margin of Qinghai-Tibet plateau: Journal of Northwest University, v. 26, n. 1, p. 99 - 104.

Lai Shaocong, Deng Jinfu, and Zhao Hailing, 1996, Volcanism and tectonic evolution in the northern margin of Qinghai-Tibet plateau: Xi'an, Science and Technology Press of Shaanxi Province, 95 - 133 (in Chinese).

Pan Guitang, Wang Peisheng, Xu Yaorong, and Zhang Canfu, 1990, Cenozoic tectonic evolution of Qinghai-Tibet plateau: Beijing, Geological Publishing House, p. 32 - 70 (in Chinese).

Ringwood, A. E., 1975, Composition and petrology of the Earth's mantle: New York, McGraw-Hill Book Company, p. 618 - 650.

Song Zhonghe, An Changqiang, Chen Lihua, and Chou Zhirong, 1986, The velocity structure of P wave for upper mantle in China continent and marginal sea: Journal of Seism., v. 8, n. 3, p. 263 - 274 (in Chinese with English abstract).

Stormer, J. R., 1975, A practical two-feldspar geothermometer: Amer. Miner., v. 60, p. 7 - 8.

Sun Yangui, 1992, Characteristics of the Miocene epoch volcanic rock zone in the north margin of Hoh Xil area: Geology of Qinghai, n. 2, p. 13 - 25 (in Chinese with English abstract).

Wood, B.J. and S. Banno, 1973, Garnet-orthopyroxene relationships in simple and complex systems: Contrib. Mineral. Petrol. v. 42, p. 109 - 124.

Xie Guanghong, Liu Congqiang, Zengtian Zhangzheng, and Qin Shuiyang, 1992, Geochemical features of the Cenozoic volcanic rocks from Qinghai-Tibet plateau and its adjacent area - evidence for existence of an ancient enrichment mantle, in Liu Ruoxin, ed., Geochemistry and chronology of the Cenozoic volcanic rocks in China: Beijing, Seismic Publishing House, p. 400 - 427 (in Chinese with English abstract).

Zeuisaki, 1972, The composition and texture (Al/Si order degree) determining for feldspar using X-ray powdered crystal method: Journal of Mineralogy, v. 10, p. 413 - 425 (in Japanese with English abstract).

Zhou Bin, Zhu Jieshou, and Chun Kinyip, 1991, Three-dimensional shear velocity structure beneath Qinghai-Tibet and its adjacent area: Acta Geophysica Sinica, v. 34, n. 4, p. 426 - 441 (in Chinese with English abstract).

Zhuang Zhen, Fu Zhuwu, Lu Ziling, Hu Jiafu, Song Zhonghe, Chen Guoying, and An Changqing, 1992, 3 - D shear velocity model of crust and upper mantle beneath the Tibetan plateau and its adjacent regions: Acta Geophysica Sinica, v. 35, n. 6, p. 694 - 709.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.