Jour. Petrol. Soc. Korea
Vol. 6, No. 2, p. 77~87, 1997

Early Proterozoic Moyitic Series in Daqingshan, Inner Mongolia : Their Characteristics and Tectonic, Magmatic and Thermodynamic Model

Lin CAO and Wei JIN

Department of Geology, Changchun University of Science and Technology, Changchun, China, 130026

ABSTRACT : The Early Proterozoic reworked rock association occurs within the Precambrian high grade metamorphic rocks in the area of Daqingshan, Inner Molgolia. In this association, the various large scale ductile deformation belts, form a nappe structure where the foliation steeply dips to north and the lineation (340°-30°) plunges at 45°-55°. This result indicates the subduction/extension with northern part thrusting over the southern part at high angle. The southern subducted microlithon has the characteristics of prograde metamorphism. The northern thrusted microlithon shows the evidence of retrograde metamorphism with decreasing pressure and increasing temperature. The main rock types of Early Proterozoic Moyites are biotite adamellite and syenogranites occurring in the form of small batholiths or stocks and alkali-feldspar granites in veins. The biotite adamellites are progressively contacted with the Archean and Early Proterozoic rocks and contain a great deal of enclaves of metamorphosed rocks, suggesting an anatexis origin. The geochemical characteristics of moyites show the typical features of anatexis granite. At middle to late Early Proterozoic time, the continent-continent collision formed the large scale thrusting and imbrication of Archean basement rocks. According to the mineral assemblage and thermobarometer of Paria *et al.* (1988) give the following P-T condition : upfaulted block; 700-710℃, 0.72-0.78 Gpa (early stage) and 600℃, 0.44 GPa (late stage), footwall block; 620℃, 0.8 Gpa (early stage), 620-840℃, 0.64-0.45 GPa (peak) and 620-630℃, 0.35 Gpa (late stage). These results suggest a clockwise P-T-t path (Jin *et al.*, 1991, 1994). According to the depth-temperature model in the compressional subduction zone and the experimental data of Wyllie *et al.* (1983), we propose a tectonic-magmatic-thermal model to account for metamorphism-anatexis of moyite occurring in subduction-shear zone.

Key Words : early proterozoic, moyite series, Daqingshan, tectonic-magmatic-thermodynamic model

INTRODUCTION

The relationship between the formation of various granites and tectonic environment is an important frontier field of earth sciences. In order to unite granite petrogenesis with plate movement we must combine the study on granite formation with thermodynamics of splitting, migration and interaction of material resulting from tectonic deformation. This paper attempts to explore the tectonic-magmatic-thermodynamic relationship of the moyitic series of Daqingshan area, Inner Mongolia, China, which was formed by the mountain building process of Early Proterozoic.

REGIONAL GEOLOGICAL SETTING

According to the structural-petrologic assemblages, metamorphism and isotopic ages, the Precambrian high-grade metamorphic rocks in the area of Daqingshan, Inner Mongolia, can be classified into the Archean, the Early Proterozoic and the reworked rock associations (Jin *et al.*, 1991, 1994). The Archean rock associations include the assemblages of granulites with charnockite, tonalitic gneiss and greenstone belt (Li *et al.*, 1986). The early Proterozoic rock associations are mainly composed of the assemblages of Al-rich gneiss and marble which have experienced the hornblende-granulite facies metamorphism. The reworked rock associations, which were formed by Early Proterozoic orogenies exerting on the Archean rocks (Jin *et al.*, 1991), have lithologic and structural dualities. They consist of Archean (biotite) hornblende monzonitic gneiss, biotite plagioclase gneiss, diopside amphibloite, charnockitic mylonite, TTG (tonalite-trondhjemite-granodiorite) mylonite and biotite granulite. The research has shown that the continent compression subduction formed not only a set of ductile shear fault zone and thrusting structural zone (Jin and Li, 1994) with nearly EW direction, but also a set of special reworked rocks and the anatectic moyitic series (Fig. 1).

The moyitic series overlain by upper and middle Proterozoic sedimentary rocks shows gradually changing, intrusive contacts with the Early Proterozoic gneiss (Li *et al*, 1986). The Rb-Sr whole rock age of syenogranite in moyitic rocks is 1880Ma, whereas the U-Pb zircon age is 1936-1913Ma, respectively. The K-Ar hornblende ages of the reworked rocks are 1872-1797Ma (Shen *et al*, 1990). Therefore, the duration of the Early Proterozoic intracontinent compression-subduction can be inferred to be 2000-1800Ma (Jin *et al*, 1991).

THE PETROGENETIC CHARACTERISTICS OF THE MOYITIC SERIES

The Early Proterozoic moyitic rocks are distributed as an EW belt (Fig. 1). The main lithology of the moyitic series is biotite monzogranite, syenogranite and alkali feldspar granite. A small-scale granodioritic rock body outcrops in Wudangzhao. The biotite monzogranite occurs in layers, lenses and small apophyses and gradually change into the wall rocks which consist of biotite-plagioclase gneiss and sillimanite-garnet-hornblende monzonitic gneiss. These rocks have granoblastic and metasomatic texture and gneissose or banded structures.

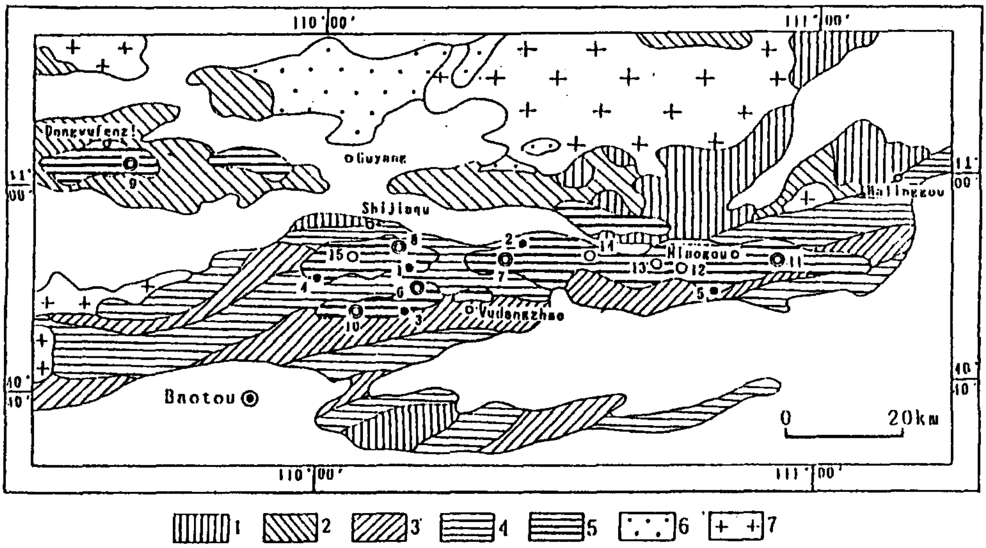

Fig. 1. The structural-lithological map of Precambrian rocks in Daqingshan, Inner Mongolia (after Jin and Li, 1994). 1; Archean charnockite-granulite system, 2; Archean tonalitic gneiss, 3; the Early Proterozoic gneiss-marble system, 4; Early Proterozoic reworked rocks, 5; Early Proterozoic moyitic rock system, 6; Proterozoic sedimentary rocks, 7; Phanerozoic granite. ● biotite monzogranite ◎ syenogranite ○ alkali-feldspar granite

The geological occurrence and petrography reflect the characteristics of in situ granite. The syenogranite mainly occurs as a small batholith or stock, while the moyite occurs mainly as dike, gradually covering into the monzogranite and is in intrusive contact with gneiss. These rocks mainly have medium to coarse grained granoblastic or porphyroblastic textures and gneissoid or massive structures. The megacrysts are microcline and microperthite which contain some early formed mineral inclusions such as biotite and plagioclase.

The attitude of gneissosity is the same as that of the reworked rock series. There are many inclusions of early Proterozoic Al-rich gneiss-marble series in biotite adamellite, such as sillimanite-garnet-honblende (biotite)-plagioclase gneiss, biotite monzonitic gneiss, two-pyroxene granulite, the Archean TTG gneiss, charnockite and garnet quartzite. There is no obvious boundary between enclaves and granites.

The main minerals of the moyitic series rocks are plagioclase, alkali feldspar, quatz and biotite. The chemical composition of K-feldspar is characterized by high alkali content (Table 1). The ratio of albite components within coexisting feldspars (Ab_{Af}/Ab_{pl}) is low. The biotite content is variable. The chemical composition of biotite is shown in Table 2. Among the compositions, MgO and TiO_2 is high, while K_2O and CaO are low with the MF [Mg/(Mg+Fe*+Mn)] range of 0.41-0.57, the average L [Al/(Al+Fe*+Mg+Mn+Ti+Si)] value is 0.21. The chemical compositions of feldspar and biotite mentioned above are similar to those in reworked granite.

The calc-alkaline granites can be divided into two series according to its source material and rock-forming mechanism (Hu and Hu, 1993):

1) Reworked granite, which is formed by metasomatism and anatexis as the result of interaction between the material of the crust and water fluid derived from the deep curst; and

2) syntectic granite, which is the product of melting, mixing and assimilation between the mantle-derived magma and the crustal materials (Table 3). The moyitic series belongs to the reworked granite according to its geological, petrographical and geochemical features.

The geochemical evolutionary features of moyitic series are as follows:

1) In Q-Ab-Or diagram, the projection points of biotite monzogranite formed during the early phase of anatexis are scattered (CaO and Qu, 1996), while those of syenogranite formed dur-

Table 1. Composition of K-feldspars

Sample No.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	total	Ab_{Af}/Ab_{Pl}
91051	64.71	0.19	20.14	0.10	0.18	0.11	0.04	0.00	0.86	14.20	100.51	0.11
P_1-72	64.76	0.00	19.87	0.10	0.00	0.00	0.00	0.00	0.64	14.37	99.75	0.08
P_1-24	64.44	0.00	20.43	0.11	0.07	0.00	0.00	0.00	0.74	14.90	100.69	0.09
A_{01}	65.60	0.00	19.27	0.00	0.00	0.00	0.00	0.00	1.47	13.59	99.93	0.22

*analyzed by an EPMA, Changchun University of Science and Technology
FeO indicates total iron.

Table 2. Composition of biotites

Sample No.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	total	MF*	L**
91051	35.08	4.06	18.07	0.20	16.15	0.00	12.19	0.00	0.15	8.57	94.48	0.57	0.23
P_1-72	36.04	3.56	15.03	0.00	25.08	0.27	8.71	0.02	0.17	5.49	94.37	0.38	0.20
P_1-24	33.53	3.84	16.21	0.00	19.51	0.31	12.23	0.00	0.22	8.83	94.67	0.52	0.21
A_{01}	34.77	2.94	14.87	0.16	23.81	0.29	9.49	0.00	0.12	7.62	94.07	0.41	0.20

*analyzed by an EPMA, Changchun University of Science and Technology
FeO, MF* and L**.indicate total iron, Mg/(Mg+Fe*+Mn) and Al/(Al+Fe*+Mg+Mn+Ti+Si), respectively.

Table 3. Comparison of characteristics between syntexis and transformation series Granitoids (After Hu, 1988)

Characteristics		Syntexis series		Transformation series		Main factors for determining differences of the two series of granitoids and their significance
		Continental crust setting		Source type		
		Island arc & Transitional	Mature arc	Endogenic	Exogenic	
Occrrence and rock association		Mainly stock, cupola and subvolcanic pipe; some batholiths developed on active continental margin; mostly composite abyssal and subvolcanic rocks closely associated; usually with cognate volcanics; lithological characters variable largely from intermediate basic to acidic.		Either simple or composite plutons closely associated with migmatites and metamorphic rocks; without cognatic volcanics and subvolcanics associated; unremarkable variations in lithology, mainly normal granites and some monzo-granites and a few K-feldspar granites.		Magmas of the transformation series having lower temperature, higher water content, unremarkable compositional variations and less emplacement capabilities than those of the syntexis series
Mineralogical features	$\frac{Ab_{Af}}{Ab_{Pl}}$	0.1-0.8, characterized by the ratios over 0.3		0.06-0.32, mostly less than 0.25		Magmas of the transformation series having lower temperatures, higher water content, unremarkerble compositional variations and less emplacement capabilities than those of the syntexis series.
	Structural parameter	$\delta(\delta')<0.45$, $T_1(0)<0.445$, $\eta<1.23$		$\delta(\delta')<0.45$, $T_1(0)>0.445$, $\eta>1.23$		
	Composition of biotite	MF>0.48, mostly; L<0.19, Ti content and oxidation index relatively high		MF<0.56; mostly<0.5, L=0.18-0.22, mostly>0.19, Ti content and oxidation index relatively low		
	Plot of MgO in biotites and whole rocks	Distributed in the syntexis series area.		Distributed in the transformation-series area.		
Geochemical evolution features	Al' value and K_2O/Na_2O ratio	increasing from early to late.		Decreasing either from autochthonous to allochthonous or from early to late		Syntexis series showing an evolution trend of mixing of deep source, intermediate-basic magmas and continental crust; transformation series showing an evolution trend of partial melting or crystal fractionation in continental crust environment; trace elements in both series recording their evolutionary processes, respectively.
	Correlation of K_2O with SiO_2	Linear positive correlation with confidence level all over 95%, mostly over 99%		With a few exceptions in migmatites, no correlation at above 95% of confidence level		
	Covariance between $(La/Yb)_n$ and $(Gd/Yb)_n$ and between $^{87}Sr/^{86}Sr$ and 1/Sr	Mostly linear and nonlinear curves observed in strongly differntiated intrusions; metasomatic alteraton leading to sample scatter		Mostly non-linear exponential or hyperbolic curves; in a few case linear plots observed in autochthonous plutons; metasomatism leading to sample scatter		

ing the main phase of anatexis, are concentrated (Fig.2). The alkali-feldspar granites

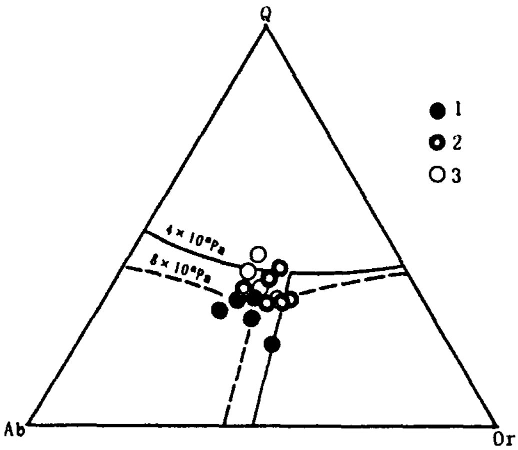

Fig. 2. Q-Ab-Or diagram of K-feldspar granitic series (after Von Platen *et al.*, 1966) (Symbols are the same as those of Fig. 1)

are plotted near the thermal minimum, suggesting that anatexis is characterized by the environment of decreasing-pressure;

2) Index of Al [Al-(Ca+Na+K)] and K/Rb change significantly and decrease with increasing SiO_2 contents (Table 4);

3) The contents of K_2O and Na_2O are reversely correlated (Fig. 3);

4) In the K_2O-SiO_2 diagram, there is no correlation between K_2O and SiO_2 as a whole, but reverse correlation exists within biotite adamellite. The reverse correlation also exists between syenogranite and alkali-feldspar granite (Fig. 4). The reverse correlations also show in P_2O_5 vs SiO_2 and K_2O/Na_2O vs SiO_2.

5) The ratios of Rb/Sr increase with the increasing SiO_2 contents (Table 4, Fig. 5);

6) Biotite monzogranite shows a low-slope evolution line, whereas other rocks a high-

Table 4. Geochemical Features of the moyitic series

	moyite	biotite monzogranite	syenogranite	alkali-feldspar granite
Al' average / range	-15.2 / 51.6~-97.2	3.4 / 51.6~-38.2	-7.9 / 18.4~-26.8	-49.3 / -1.6~-97.2
K / Rb	421.8 / 1033~196	584 / 1033~196	341 / 421~278	286 / 327~237
K_2O / Na_2O	1.39 / 1.94~0.83	1.19 / 1.61~0.83	1.58 / 1.94~1.09	1.37 / 1.62~1.15
ΣREE (ppm)	192.4 / 462.4~45.4	228.1 / 462.4~124.0	275.4 / 453.5~162.5	64.9 / 89.1~43.4
Rb (ppm)	112.6 / 35.2~158.5	77.3 / 35.2~147.0	127.8 / 90.7~158.5	146.0 / 141.6~153.3
Rb / Sr	0.49 / 0.13~1.61	0.21 / 0.13~0.34	0.55 / 0.23~0.81	0.84 / 0.44~1.61
LREE / HREE	8.7 / 3.2~15.9	6.6 / 3.2~10.4	9.0 / 5.1~15.9	10.7 / 5.8~15.3
K_2O-SiO_2 correlativity	dispersal	obscure negative correlation	linear negative correlation between the two rocks	
P_2O_5-SiO_2 correlativity	partial negative correlation	linear negative correlation	as the above	
coordination among elements	nonlinear coordination and similiar evolutionaary trends			

Al'=Al-(Ca+Na+K), the number of atoms; data after Cao and Qu(1996).

slope one in MgO-DI diagram (Fig. 6). This result suggests that the former is in situ type, while the latter is semi-in situ and allochthonous type granite;

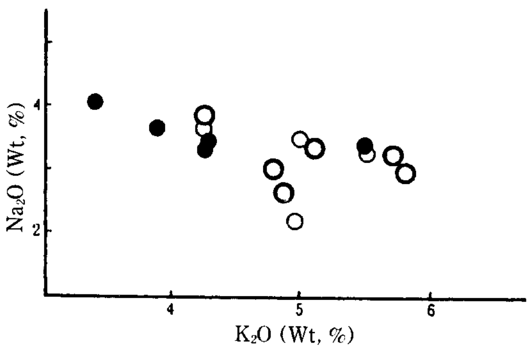

Fig. 3. K_2O-Na_2O correlation diagram. (Symbols are the same as those of Fig. 1)

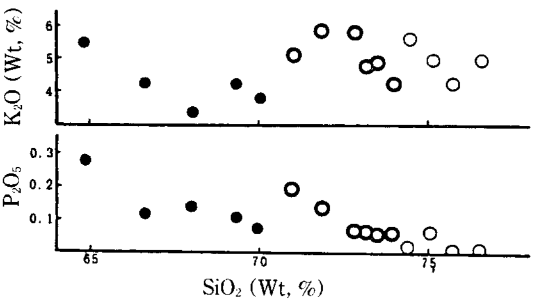

Fig. 4. The relationship of K_2O-SiO_2 and P_2O_5-SiO_2 (Symbols are the same as those of Fig. 1)

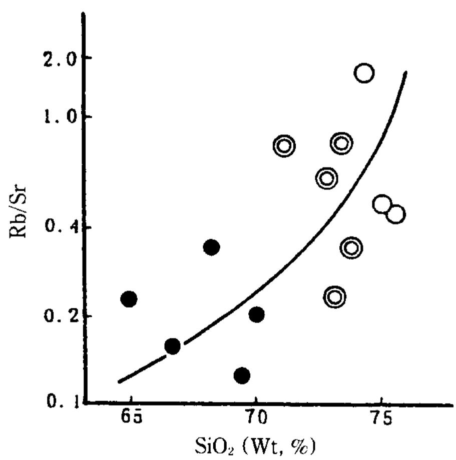

Fig. 5. Diagram of Rb/Sr vs SiO_2 (Symbols are the same as those of Fig. 1)

7) Rae earth elements and trace elements are not linearly correlated (Fig. 7);

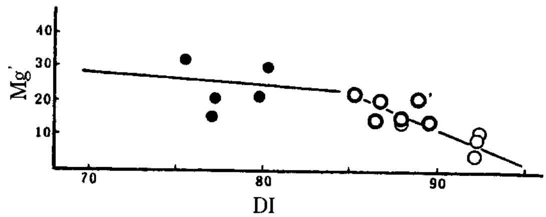

Fig. 6. Diagram of Mg (Niggli value) vs DI (differentiation Index) (Symbols are the same as those of Fig. 1)

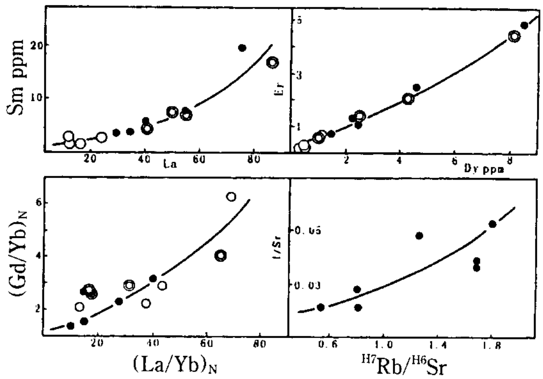

Fig. 7. The relatioship between trace elements and rare elements (Symbols are the same as those of Fig. 1)

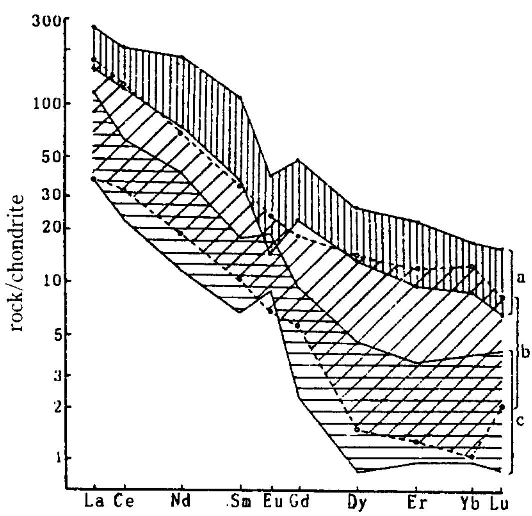

Fig. 8. Distribution pattern of the REE in moyitic series a; biotite monzonitic granites, b; syenogranites, c; alkali feldspar granites

8) The compositional trends of rare earth elements are largely variable because the compositions of the source rocks are complex (Fig. 8);

THE TECTIONIC ENVIRONMENT OF MOYITIC MAGMA FORMATION

The triggering mechanism for the emplacement of granitic magma may be attributed to the action of a large scale compressive faulting (Zhao, 1980; Leak, 1983; Wang, 1985; Mo, 1987). The Early Proterozoic reworked rock associations in the Daqingshan area developed with a series of thrust tectonic belts characterzied by ductile deformation zone, a large scale stretching lineation and A-type fold group. The schistosity and gneissosity strike nearly E-W and dip to north; the orientation of lineation is about 340°-30° with the plunging angle of 45°-55°. Lineation is defined by hornblendes, pyroxenes and elongated garnets. The large scale lineation is presented by the felsic bar-structure. The A-type fold group mainly exists in biotie-hornblende gneiss and their regional fold hinges have the same orientation as the lineation. The voluminous, deformed granitic veins have synstructural features. The shear sense of the thrust belt determined from various deformational fabrics indicate that the northern wall (the thrust wall) was thrust up to the southern wall (subducted wall) at a high angle.

The histroy of the Precambrian crustal evolution has shown that a set of muddy and sandy-marl-carbonate sediments were deposited in this area during the early stage of the Proterozoic (Jin *et al.*, 1991). The stage of continental orogenic belt was established after the continent-continent collision and subduction began from the early Proterozic. There are main events occurring at this time include collision, metamorphism and the emplacement of anatectic granite (Jin *et al.*, 1991).

The Collisional Event

The continent-continent collision thickened the Archean craton basement through subduction/thrusting on a large scale, forming a large thrusting rock slabs. The Proterozoic sedimentary rocks were involved in foreland thrusting system, subducted into the deeper part of the crust and formed the high pressure-low temperature metamorphic rocks (Jin *et al.*, 1991). The main collision event ended in 2200-2000 Ma according to the isotopic age of Al-rich gneiss and the cooling rate of the late crust.

The Metamorphic Event of the Orogenic Belt

The mineral assemblages of high pressure-low temperature formed during the collision transform into those of low pressure-high temperature because the thrust belt lies in a tectonothermal environment of decreasing pressure and increasing temperature. This thermal regime resulted from the restoration of isothermal planes by radiogenic heating.

The change in mineral assemblages define a clockwise P-T-t path. The changes of temperature and pressure are different between thrusted and subducted parts. The subducted slab apparently shows a progressive metamorphism and is characterized by the main mineral assemblage of Hb+Bi+Pl+Q; and Hy_1+DI+Gt+Pl in early period, Hy_2+Hb+Pl_2+Bi in the later period. The metamorphic conditions calculated from Paria *et al* (1988) and Newton *et al.* (1982)'s, geothermobarometer are: T=620℃, P=0.8 GPa in the early period; T=650-840℃, P=0.64-0.45 GPa in the main period; T=620-630℃, P=0.35 Gpa in the later period. The Early Proterozoic granulite represented by Al-rich gneiss is considered to have formed in the above metamorphic conditions.

Some Archean rocks involved in the footwall of the thrust slab became the reworked rocks through the superimposed metamarophism and show the same P-T-t evolution as that of Al-rich gneiss. The thrust slab shows obviously retrograde metamorphism and is characterized by the mineral assemblage of Bi+Hb+Pl+Q.

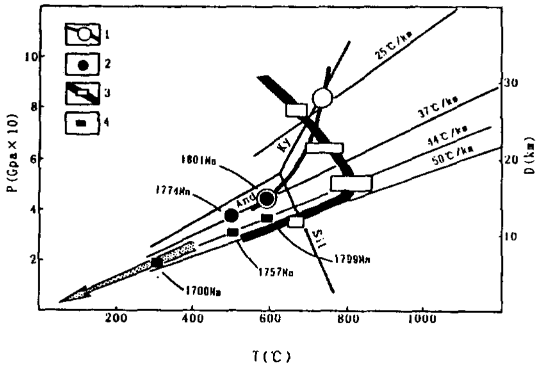

Fig. 9. P-T-t evolution of the Early Proterozoic tectonic uplift stage in the Daqingshan area (after Jin and Li, 1994). P-T-t paths of the thrust and subducted belts determined from metamorphic minerals; the cooling age determined from the closure temperature of 40 Ar/39 Ar: 1; The P-T-t path of subducted belt, 2; hornblende, biotite and pyroxene from left to right, 3; The P-T-t path of the thrust belt, 4; hornblede on the left, pyroxene on the right. Thin lines are the geothermal gradient; that of thrust slab is 25°C/km (early period) and 37°C/km (peak period) and that of subducted slab is 25°C/km (early period) and 44-50°C/km (peak period). Al_2O_3 phase boundary after Richardson *et al.*, (1969).

The early Hy, Di and Gt occur in the form of relic minerals. The metamorphic conditions of the thrust slab are: T=700-710°C, P=0.72-0.78 GPa in the early; T=600°C, P=0.44 GPa in the late stage. This result suggests that both pressure and temperature decreased along the retrograde path (Fig. 9).

ANATEXIS

According to the theory of cooling and closure temperature suggested by Dodson (1973) and the $^{40}Ar/^{39}Ar$ age calculations of biotite, hornblende and pyroxene for determining the colling rate and the uplifting rate of the crust during the Early Proterozoic orogenic event in the Daqingshan area, only the subducted slab of the Precambrain metamorphic rocks underlain at the depth of 30-40 km began to uplift. During this process, the pressure decreaed from > 0.8 Gpa to < 0.35 Gpa and the temperature increased from 600-700°C up to 840°C at first and then fell down to 500°C.

As seen from the Figure 9, the uplifting footwall slab in the depth of 30-15 km is still in pressure-decreasing and temperature-increasing environment and its temperature increased from 600°C to 840°C. The $^{40}Ar/^{39}Ar$ closure temperature of minerals shows a geothermal gradient of up to 44-50°C/km, indicating that the T can reach over 990°C in the depth 20-30 km. The temperature of the hanging wall is over 600°C although it belongs to the retrometamorphic environment of decreasing temperature and pressure. The closure temperature of the minerals shows that geothermal gradient in the hanging wall may reach 37°C/km. Thus the temperature at the depth of 20 km may reach about 700°C. The facts mentioned above suggest that there was a melting condition of crustal granulite (Wyllie, 1981). The Archean TTG gneiss, the Early Proterozoic Al-rich gneiss and reworked rocks in the area contain many hydrous minerals such as hornblende and biotite, therfore, fluids released from these rocks are mainly H_2O-fluid, which is prerequisite for anatexis. In addition, a lot of H_2O-fluid can be released from the continental blocks through the granulite facies metamorphism. The experiment by Wyllie *et al.* (1976) showed that when the amount of H_2O is beyond 2.5% in the granite system, the crystallization of biotite is earlier than that of K-feldspar. There are many biotite inclusions within the K-feldspar phenocrysts of syenogranite, suggesting the crystallization of biotite earlier than K-feldspar. Obviously, water content of the system was beyond 2.5% during the formation of the syenogranitic magma. The melting experiment of the crustal gneiss by Wyllie (1983) suggested that gneiss with 2% H_2O can produce granitic magma under the condition of middle-lower crust (T=900°C).

TECTONIC-MAGMATIC-THERMODYNAMICAL MODEL FOR FORMATION OF MOYITIC SERIES

According to the condition of temperature and pressure experienced by the upper crust duing the Early Proterozoic orogenic process, we have established a model for generation and emplacement of granitic magma (Fig. 10).

Four areas are divided according to metamorphic degree and anatectic condition:

1) epimetamorphic area, at depths of 12-15 km and temperatures of about 450℃, is characterized by greenschist-lower amphibolite facies metamorphic rocks which have been subsequently eroded out;

2) amphibolite facies-migmatization area, at depths of 15-20 km and temperatures of 450-650℃, is mainly characterized by amphibolite-faceies metamorphism and metasomatism. Migmatites are common in this area;

3) anatexis area, at depths of 20-28 km and temperatures of 650-900℃, is characterized by anatexis and formation of granitic magma;

4) granulite facies area, at depths greater than 28 km and temperature of 900℃, formed granulite facies rocks.

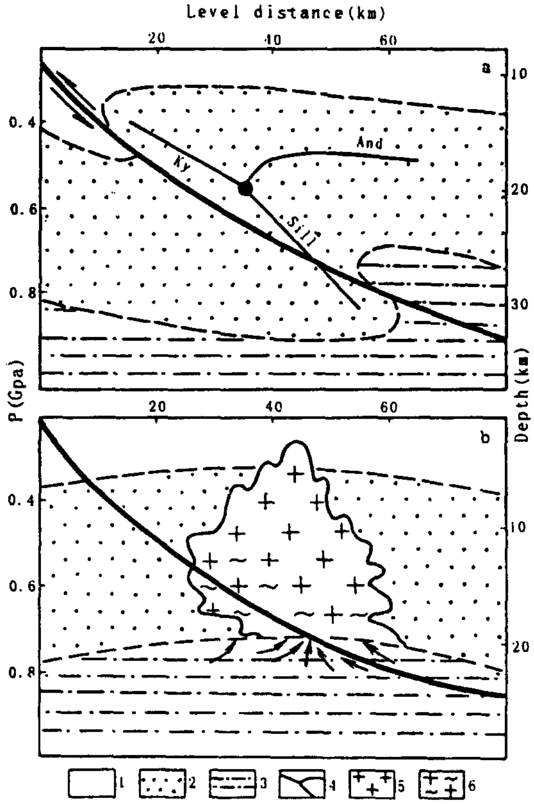

Fig. 10. Tectonic magmatic-thermodynamic model of moyitic series rocks 1; epimetamorphic area, 2; amphibolite facies, 3; granulite area, the flow direction of H_2O-fluids released from granulite facies area, 4; phase boundary of Al_2O_3, 5; syenogranite and alkali granites, 6; biotite adamellite, the dashed line represents the transition between each zone. a; subduction stage, with different grade of metamorphism at various depths, b; post-subduction stage, local anatexis resulting from the input of a small amount of H_2O

The production of the large scale anatexis can be triggered by the following: the addition of H_2O-rich fluids released from hydrous minerals, the decompression lowering the melting point of eutectic components and the heating of the footwall rocks slices from the deep subduction with the uplifting of geothermal gradient and the effect of geothermal isothermal surface restoration. During the early period of anatectic process, metasomatism is dominant and the limited melting can form in situ, biotite monzogranitic magma. As the large amount of H_2O-rich fluids may be released during the granulite facies metamorphism in the deep crust, the anatexis can result in the formation of granodioritic melt within the TTG gneiss. During the peak period of anatexis, the syenogranitic magma can be generated and form semi-in situ (or allochthonous) syenogranite through a short-distance movement.

When the metamorphic rocks were uplifted to a shallow depth and temperatures no longer increased or decreased, the anatexis ended. The crystalline differentiation during the late period of the anatexis resulted in a small scale alkali-feldspar granitic rocks.

ACKNOWLEDGMENTS

This study was funded by the basic research project of Mininstry of Geological and Mineral Resources, China (8502209). We sincerely thank Prof. Lin Qiang for his critical reviews. Sincere thanks are also due to Drs. Liu Li, Wu Fuyuan and Cho, M for their perfect translation from Chinese to English.

REFERENCES

Cao Lin and Qu Yixiu, 1996, Anatexis origin and tectonic environment of Early Proterozoic K-feldspar granitic rocks in Daqingshan area, Changchun: Journal of Changchuun University of Earth Sciences, Vol. 26, No. 1, 24-30.

Dodson M. H., 1973, Closure temperature in cooling geochronological and petrological systems. Contrib. Mineral. Petrol., 40, 259-274.

Hu Zhihong and Hu Shouxi, 1993, Compression-subductions and twin granite belts, Beijing: Geological Publishing House, 1-43 : 167-169.

Jin Wei, Li Shuxun and Liu Xishang, 1991, The Characteristcs and meta-dynamics of the Early Precambrian high grade metamorphic sequences in Daqingshan, Inner Mongolia. Acta Petrologica Sinica. No. 4, 27-35.

Jin Wei and Li Shuxun, 1994, The lithological association and geological features of early Proterozoic orogenic belt in Daqingshan, Inner Mongolia; Qian Xianglin and Wang Renmin. (Eds), Geological evolution of the granulite terrain in north part of the North China craton, Beijing : Seismological Press 32-42.

Lake, B. E., 1983, Ultrametamorphism, migmatite, melting and the formation of granitoids, in migmatites. Melting and metamorphism. (Eds), M. P. Athertion and C. D. Gribble. Shiva Publishing Limited, Cheshire, UK.

Li Shuxun, Zhang Luqiao, Sun Deyu, 1986, The Archean geological characteristics and mineralization of the Dongwufenzi-Zhulagou area, Inner Monglia. Research Report (unpublished).

Mo Zhuxun, 1987, The primary studies on the formation mechanism of the composite granite belts in southern China. Gangdong Geology, Vol. 2(2) : 1-12.

Newton R. C and Penkins D., 1982, Thermodynamic calibration of geobarometers based on the assemblages garnet-plagioclase-orthopyroxene (chinopyroxene)-quartz. Am. Mineral., Vol. 67.

Paria D., Bhattacherya A. and S. K., 1988, The reaction garnet+chinopyroxene+quartz=2 orthopyroxene+anorthite : A potential geobarometer for granulites. Contrib. Mineral. Petrol. Vol. 99.

Richardson S. W., Gilbert M. C. and Bell P. M., 1969, Experimental determination of Kyanite-andalusite and andalusite-sillimanite equilibria : the aluminum silicate triple point. Am. Jour. Sci., Vol. 267, 269-272.

Shen Qihan, Zhang Yinfang, Gao Jifeng, 1990. The Archean metamrophic rocks in the middle-southern Inner Mongolia. Journal of Geological Academy of China, No. 21, Beijing : Geological publishing House.

Von Platen H. and Holler H., 1996, Neues Jb Miner. Mh 106-130.

Wang Dezi, Ma Ruishi, Wang Xiyin, *et al.*, 1985, Studies on the relations between fault regional metamorphism and migmatization and granitization. Journal of Nanijing University, No. 21(3).

Wyllie P. J., 1981, Plate tectonics and magma genesis. Geol. Rundsch., Vol. 70, 128-154.

Wyllie P. J., 1983, Experimental strudies on biotite and muscovite-granites and some crustal magmatic sources, in migmatites, melting and metamorphism (Ed. M. P. Atherton and C. D. Gribble) Shiva Pulb. Limited. Cheshire, UK., 12-16.

Wyllie P. J., Huang, W. J., Stern, C. R. and Maaløe, S., 1976, Granitic magmas : possible and impossible sources, water contents and crystallization sequences. Can. J. Earth Sci., Vol. 13, 1006-1020.

Zhao Bin 1980. The anatectic mechanism from faults and its implications. Journal of Changchun University of Earth Sciences, No. 2, 33-40.

(책임편집 : 조문섭)

내몽고 다퀑샨내의 초기원생대 모이아이트계열 : 특성과 지구조, 마그마 그리고 열역학적 모델

曹林 · 金巍

중국 장춘대학 지질학과

요 약 내몽고 다퀑산일대에는 초기원생대의 선캠브리아대 고변성암대가 존재한다. 이들은 대규모 연성변형대로 북쪽으로 급경사진 엽리와 340°-30°<45°-50° 방향의 선구조가 보이는 나페구조를 형성한다. 이는 섭입/팽창동안 북쪽지역이 남쪽지역 위로 드러스트에 의해 올라갔음을 지시한다. 남쪽의 침강된 지역은 전진 변성의 특징을 보여준다. 북쪽의 드러스트 된 지역은 압력 감소와 온도 상승에 따른 후퇴 변성의 증거들이 나타난다. 초기원생대 모이아이트질 암상은 소저반상을 이루는 흑운모 아다멜라이트, 섬장화강암과 맥상의 알카리-장석 화강암으로 구성되어있다. 흑운모 아다멜라이트는 시생대와 초기원생대의 암석과 점이적인 접촉을 보이며, 변성암의 포유물을 다량 함유하여 아나텍시스기원을 지시한다. 모이아이트질 암석의 지화학적 특성은 전형적인 아나텍시스기원을 보인다. 초기원생대의 중기에서 후기에 대륙-대륙 충돌은 대규모 드러스트와 시생대 기저암의 인편상 작용(imbrication)을 일으켰다. 광물조합과 Paria *et al.*(1988)의 지온지압계를 이용하여 P-T 환경은 다음과 같다: 상부블록; 700-710℃, 0.72-0.78 GPa(초기상태)와 600℃, 0.44 GPa(후기상태), 하부블럭: 620-840℃, 0.64-0.45 GPa(최대변성작용), 620-630℃, 0.35 GPa(후기상태). 이 결과는 시계방향의 압력-온도-시간경로를 지시한다(Jin *et al.*, 1991, 1994). 횡압력하의 섭입시 깊이-온도모델과 Wyllie *et al.*(1983)의 실험결과를 이용하여 섭입대-연성대 내에서 발생하는 변성작용과 아나텍시스 작용에 대한 지구조-마그마-열역학적모델은 제시하였다.

핵심어 : 초기원생대, 모이아이트계역, 다켕샨, 지구조-마그마-열역학적 모델