Tectono-thermal evolution of middle-south section of the Da Hinggan Mountains*

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Abstract The tectonic settings of the different stages of the magmatic activity in the middle-south section of the Da Hinggan Mts. are analyzed through measuring the isotopic ages of the Mesozoic volcano-plutonic rocks from this area, and thus the tectono-magmatic evolution series are consequently determined as the initial mantle upwelling marked by the Late Triassic invasion of basic-ultrabasic rocks containing mantle-source enclaves, middle-upper crust extension marked by intrusion of the Early-Middle Jurassic diobase dike swarms, dramatic ruption of the Late Jurassic trachitic volcanic rocks, the Early Cretaceous nonorogenic alkalic-subalkalic granite invasion and the formation of the basic dike swarms and basalts. It is thus inferred that the uprise of the Da Hinggan Mts. in the Mesozoic is closely related to the upwelling of the deep magma in the mantle upwarping settings.

Keywords: **tectono-thermal evolution series, volcano-plutonic rocks, mantle upwelling.**

The Da Hinggan Mts. are distantly opposite the Taihang Mts. with Yanshan Chain in between, both depicting the main tectonic framework of East China. The Da Hinggan Mts. are also an important structural belt in the geophysical sense. Over 75% area of the Da Hinggan Mts. is covered with the Mesozoic magmatite, forming a significant polymetallic ore belt in North China bearing tin, copper, lead, and zinc (fig. 1). Study on the Mesozoic tectono-thermal evolution of the Da Hinggan Mts. should be valuable for understanding the continental lithosphere evolution as well as resources in East China.

The middle-south section of the Da Hinggan Mts. refers to the part south of Wulanhaote, and the geographic Da Hinggan Mts. extend as far south as the north bank of the Xar Moron River. Geologic surveys reveals that the Mesozoic strata and tectonomagmatic evolution of the area south of Chifeng from Kalaqinqi to Ningcheng are much similar to those of the middle-south section of the Da Hinggan Mts., thus this area is also included in the present study.

1 Settings of Mesozoic tectonic evolution

The Da Hinggan Mts. obliquely bestride the Hinggan-Mongolia orogene with its middle-south section being the intersectional part of the two. the Hinggan-Mongolia orogene is in turn a part of central Asia-Mongolia-Ochotsk orogenic zone, whose predecessor used to be a part of the ancient Asian Ocean, which began its development in the Late Precambrian within the interconti-

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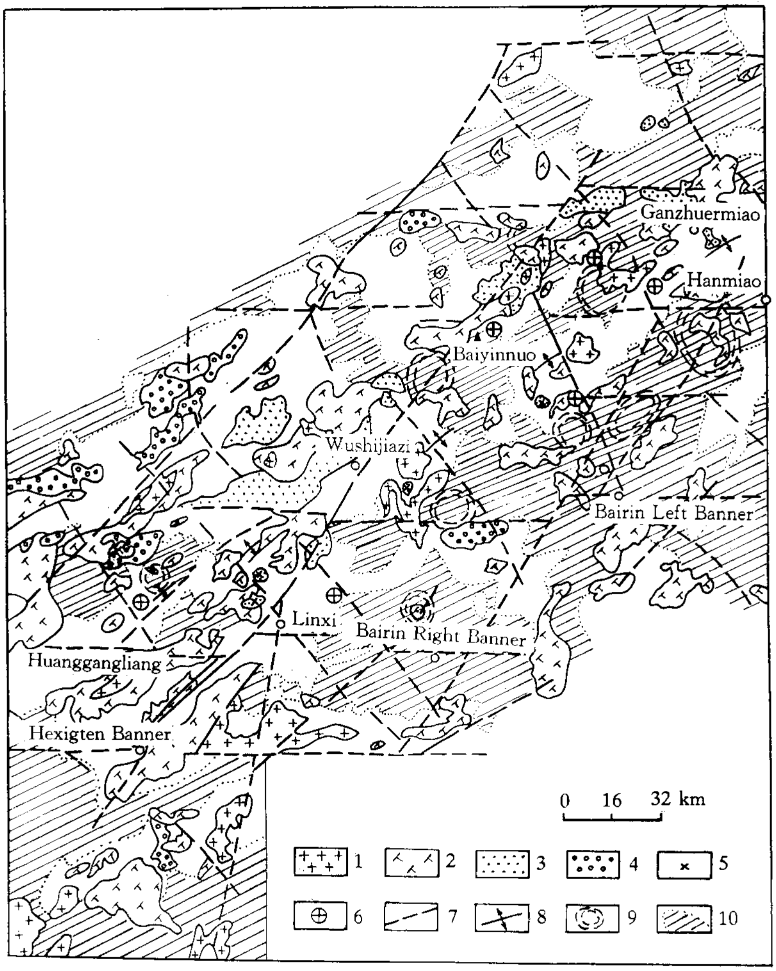

Fig. 1. Mesozoic tectono-magmatic rocks map in the middle-south section of the Da Hinggan Mts. (revised according to data from Inner Mongolia Bureau of Geology). 1, Early Cretaceous granite; 2, Late Jurassic granite with a small ammount of Middle Jurassic granite; 3, Late Triassic plutonic rocks; 4, palaeozoic granite; 5, mantle sourced or mantle source enclave bearing plutonic rocks; 6, large-scale industrial polymetallic mineral deposits; 7, measured or inferred faults; 8, anticlinoria axis; 9, volcanic apparatus; 10, Late Jurassic volcanic rocks.

nental ocean basin among North-China Plate, South Mongolia microcontinent and Siberian Plate. The ancient Asian Ocean finally closed in the Late Devonian, and many microcontinents also converged in the process, with some sections of the ocean basin eventually transforming into continental crust with deposits of detrital materials of terrigenous origin or volcanic materials. The collision orogenic action accompanying the suture of the plates is relatively weak, with features of a "soft collision and weak orogeny". The unconformable contact at the bottom of the Famennian, Upper Devonian, the remobilized granite of 369—315 Ma, and a suite of low-pressure facies series metamorphic rocks mark an orogeny-related process of the silic crust thickening. Both sides of the suture line have been mostly in an epicontinental sea environment, which is devided by the east-west rising belt, since the Middle Carboniferous. Most of those troughs are synsedimentary fault basins receiving a volcano-sedimentary series of 3 000—5 000 m. Noticeable are the eight magmatic rock belts of rift features in the Hinggan-Mongolian orogene and both sides appearing at the end of the Early Permian[1]. Among them the Gobi-Tianshan-Baolige belt passing Erlianhaote has the best continuity, and its well-developed bimodal volcanic rocks are represented by alkali rhyolite-bearing riebeckite, trachyliparite, and basalt. From Huanggangliang to Dashizhai near Wulanhaote in the southern Hinggan zone there also develops a suit of bimodal continental-rift volcanic rocks formation. The pillow basalt in the Huanggangliang area has a $^{87}Sr/^{86}Sr$ value of 0.704 2—0.705, indicating a sea-floor volcano eruption with a deep origin. Then a suite of alkali granite belt of a quite large-scale invades the orogene from Gobi, Tianshan to Hinggan belt during the end of the Late Palaeozoic to the beginning of the Triassic[2]. Bimodal volcanic rocks and alkali granite may be considered formed by posttectonic extenstion. However, the magmatic activity of so large a scale does implicate the relatively low degree of consolidation of the young continental crust of the orogene as well as reflects the rather strong power of the upwelling of the deep materials. Therefore, the posttectonic extension of the Hinggan-Mongolian orogene is not only a relaxing adjustment, but also closely related with the active upwelling of the materials from the deep lithosphere, which reflects an active crust-mantle interaction and Moho adjustment, showing that the area has entered a tectonic transformation stage[3].

2 Mesozoic tectono-thermal evolution

2.1 Early Mesozoic initial mantle upwelling (T)

This area is mostly in an upwelling and denudation state in the Triassic, and there may be local Early Triassic sediments. Yet a series of events come into being in the depth in this period. First occurs the Early Triassic muscovite or muscovite-biotite-granite invasion: a suite of light color muscovite or muscovite-biotite-granite intermittently crops up in a range of 100 km along the main crest of the Da Hinggan Mts. from Baitazi to Ganzhuermiao, which invade the Upper Permian Linxi Formation and cause the Linxi Formation sand slate to metamorphose into sericitized felsic schist. The muscovite and felspar in the granite orientedly spread. The granite contains magnetite, garnet, fluorite, and monazite, with unsaturated H_2O, high SiO_2 (75%), K_2O higher than Na_2O, low CaO, supersaturated aluminium ($A/CNK > 1.1$, with 4%—5% normative mineral corundumite), low ΣREE ($19.41—22.14 \times 10^{-6}$), nearly even REE distribution pattern and strong europium negative anomaly (δEu 0.036). Thus it is a suite of peraluminous granite forming from partial melting of argillaceous rocks. Experimental petrology data demonstrate that the muscovite granite magma originates from partial melting of the argillaceous rocks in 20—40 km depth[4]. It is inferred that the Early Triassic middle-lower crust was formed from partial melting by the underplating in the initial stage of the mantle upwelling. Upwelling of the asthenosphere should promote activeness of the mantle source magma. The authors have recently recognized the in the middle-south section of the Da Hinggan Mts. a series of mostly Late Triassic ultrabasic rocks and intermediate-basic rock bodies bear mantle-source enclaves (table 1), including the dunite and spinel-containing harzburgite and gabbro in Ganzhuermiao area, phlogopite-olivine websterite and gabbro enclaves contained in diorite in Luotuochang, uralitized pyroxenite in Haisuba, gabbro in Balengshan, olivine-bearing norite enclaves in monzodiorite in Lanjiayingzi, and websterite enclaves in gabbro in Dalugou. They have the following features: (i) low initial ratio of strontium: 0.703 5—0.704 9, (ii) low ε_{Sr}: −6—10, (iii) $\varepsilon_{Nd}(t)$: 0.5—4.02, (iv) high Cr and Mg in the ultrabasic rocks, for example: Cr_2O_3 content in the Luotuochang pyroxenite is 1.3%—1.6%, and in the Ganzhuermiao dunite Cr 3 230 $\times 10^{-6}$, Ni 1 930 $\times 10^{-6}$, Co 124 $\times 10^{-6}$, and MgO 42%, with spinel contained in harzburgite, revealing the mantle source of those rock bodies or enclaves. (v) It is noticeable that the carriers of the enclaves in this area are all diorite, which come from partially melted lower crust, and that the enclaves are mainly refractory remnant of the mantle rocks in the lower crust and have not come directly from the mantle (for example, that microscopic examination reveals some of the "gabbro" enclaves are products of early crystallized pyroxenite contaminated by later diorite). That means that in the initial mantle upwelling stage the extension process is limited, and hence the upward speed of the deep materials from the crust-mantle boundary is much lower that that of the Cenozoic basalt, having sufficient chance for material exchange with the continental crust. Such a phenomenon of mantle source enclave bearing intermediate-basic magma can also be found in North China craton and Taihang Mts. area. Zang et al.[8] describe the mantle source enclaves in Yanshan-period (133—129 Ma) diorite and amphibole gabbro in Shexian County of Taihang Mts. area, pointing out that it is andesitic magma instead of alkalic basalt magma that is produced because the mantle upwelling causes general decrease of the temperature and pressure in the upper mantle and the proportion of the partial melting upper mantle is even smaller. This also otherwise proves that North China, including the area concerned, is under an extensional environment controlled by mantle upwelling for about 100 million a from the Early Mesozoic (230 Ma) to Late Mesozoic (130 Ma).

Table 1 Isotopic ages of Mesozoic magmatic rocks and volcanic rocks in middle-south section of the Da Hinggan Mts.

Location	Lithologic character	Age/Ma		Method	$^{87}Sr/^{86}Sr$	
Jilinba	diabase	K1	100.6±2.7	K-Ar	0.705 3	
Kulongshan[a)]	quartz porphyry	K_1	103.9	U-Pb		
Yaoerya	moyite	K_1	115.1±4.1	U-Pb	0.704 9	
Senggengbanan	Porphyraceous granite	K_1	117.3±7.1	U-Pb	0.708 8	
Shuangfatun	Alkali basalt-trachyandesite	K_1	121.9±3.9	Rb-Sr	0.704 7	0.996 6
Nianzishan[5]	alkali-miarolite	K_1	123±8.6	Rb-Sr		
Baerzhe[6]	alkali-miarolite	K_1	125.2±2	Rb-Sr	<0.705	
Laofangshen 1	porphyritic ranite	K_1	127.5±4.2	Rb-Sr	0.705 6	0.997 5
Xiaohanshan[b)]	moyite	K_1	131.9	Rb-Sr	0.705 6	
Laofangshen 2	moyite	J_3	136.6±8.6	Rb-Sr	0.704 9	0.991 2
Jiulianshan	biotite adamellite	J_3	137.5±4.7	Rb-Sr	0.704 2	0.997 4
Huanggangliang[a)]	moyite	J_3	142.05±7	Rb-Sr	0.702 8	0.993 9
Dongshan	pyroxene andesite-liparite	J_3	142.37±3.8	Rb-Sr	0.705 4	0.998 9
Maanzi[d)]	moyite	J_3	155.4	Rb-Sr	0.704 6	
Banqiaogou	moyite	J_3	166.79±4.5	Rb-Sr	0.708 6	
Fulingou	diabase	J_2	170.4±5.2	K-Ar	0.704 4	
Baiyinnou 1[a)]	monzodiorite	J_2	171	Rb-Sr	0.703 3	
Erdaogou	andesite	J_2	178.79±7.6	Rb-Sr	0.705 8	0.995 9
Luojiaying	granodiorite	J_2	179.9±6	Rb-Sr	0.707 2	0.998 2
Shuguang	granite	J_1	185.3	U-Pb	0.705 8	
Fulingou	diabase	J_1	199.6±6.7	K-Ar	0.703 6	
Haisuba	uralitized pyroxenite	J_1	202.14±1.4	Rb-Sr	0.704 4	0.999 7
Heishantou	biotite granite	T_3	213.6±8.63	Rb-Sr	0.704 9	0.995 7
Baiyinnou 2	quartz monzodiorite	T_3	217.5±9.5	U-Pb	0.710 9	
Lanjiayingzi	olivine-bearing norite	T_3	221±30	Rb-Sr	0.704 9	0.957 5
Balengshan	babbro	T_3	228.46±6.8	Rb-Sr	0.703 5	0.996 0
Luotuochang [7]	olivine pyroxenolite-babbro	T_3	229±2.5	Rb-Sr	0.703 8	
Naoyangwula[a)]	gabbro	T_2	241	U-Pb		
Shuguang	muscovite granite	T_1	242.8	K-Ar		

a) Age data from previous authors (successively by Li[5], Wang[6] and Wang, Bao, the Inner Mongolia Third Geological Survey Team, and Xu[7]). The remainder are by the present authors, with the measurement carried out by Qiao, Zhang, and Wu. b) Age for the Kalaqinqi area of Chifeng.

2.2 Dike swarms——evidence of upper lithosphere extension (J_{1-2}, K_1)

From Fulingou to Jilinba northeast to Huanggangliang, a place 2 034 m above sea level in the Da Hinggan Mts., there are a series of diabase dikes distributed in an area of about 100 km^2 and forming compact dike swarms. As many as one hundred dikes are located in Fulingou of 2 km length, among which the single dikes are 1—2 m wide and 100—1 000 m long and the complex dikes 20—70 m wide. The edges of the dikes are generally smooth and straight, somewhere saw-toothed or with branches sagging on both sides like fir trees, reflecting conjugate tension fracture systems caused by upward forces. The petrological composition and degree of crystallinity show a tendency of the dike swarms expanding symmetrically toward both sides. K-Ar dilution method is used to determine the ages of the dike swarms (table 1), finding out that the Fulingou group of NW 330° has an age of 199.6 Ma (J_1), characterized by complex dikes and extension features; the group of NW340°—350° has an age of 170.4 Ma (J_2), composed of diobase and diobase-porphyrite and characterized by extensive stretching and sinistral shearing tensile features, and the Jilinba group of NNE has an age of 100.6 Ma, stretching long and spreading wide. This means that the area experiences an anticlockwise rotation as well when the dike swarms are formed under extension controlled by upwelling from the depth.

The petrochemical and geochemical characteristics of the dike swarms are as follows: they belong to tholeiite series; 47%—52% SiO_2, 1.2%—2.25% TiO_2, low K_2O (0.8% in average), $Na_2O > K_2O$; even chondrite-normalized rare-earth elements distribution patterns, relatively low ΣREE ((70—102) $\times 10^{-6}$), 0.703 6—0.704 8 $^{87}Sr/^{86}Sr$, showing an origin of the magma in the undifferentiated mantle. Trace element Zr/Y-Zr and F_1-F_2 relation of pyroxene reveal them as intraplate basalts (fig. 2) comparable with typical continental tholeiite (table 2).

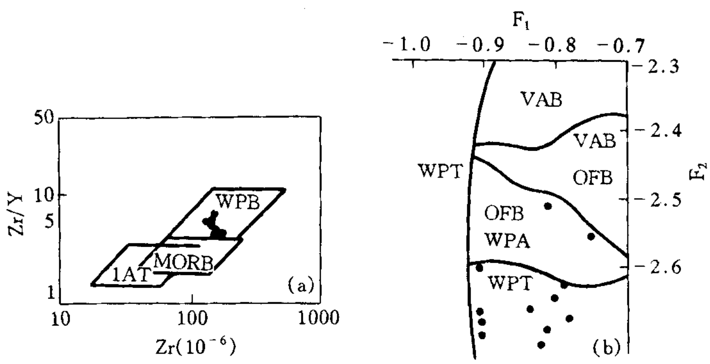

Fig. 2. Structural settings for Diabase Formation. (a) Zr-Zr/Y diagram (according to J. A. Pearce et al., 1979); (b) F_1-F_2 diagram of clinopyroxenite (according to E. C. Nisbet et al., 1997). VAB, Volcanic arc basalt; OFB, oceanic island basalt; WPT, intraplate tholeiite; WPB, intraplate basalt; MORB, mid-oceanic ridge basalt; IAT-island arc basalt. $F_1 = -0.120\ (SiO_2) - 0.080\ 7\ (TiO_2) + 0.002\ 6\ (Al_2O_3) - 0.001\ 2\ (FeO^*) - 0.002\ 6\ (MnO) + 0.008\ 7\ (MgO) - 0.012\ 8\ (CaO) - 0.041\ 9\ (Na_2O)$; $F_2 = -0.049\ 0\ (SiO_2) - 0.081\ 8\ (TiO_2) - 0.212\ (Al_2O_3) - 0.004\ 1\ (FeO^*) - 0.143\ 5\ (MnO) - 0.002\ 9\ (MgO) + 0.008\ 5\ (CaO) + 0.016\ 0\ (Na_2O)$.

2.3 Violent deep source volcanic activity (J_3)

The Late Jurassic volcanic rocks compose the main body of the Da Hinggan Mts. The volcanic activity takes place alternately in volcanic overflow facies and explosion facies, forming moniliform volcanic apparatus located nearly at equidistance, reflecting that the Late Jurassic

Table 2 Comparison of compositions of dike-swarms in present area and continental tholeiite

	Continental tholeiite[a)]	Dike-swarms in the area[b)]
TiO_2	1.5—3.2	1.2—2.25
FeO^*/Mg	1.1—3.5	1.1—2
K/Rb	120—500	<441
Rb/Sr	0.015—0.4	0.12—0.4
$U/K \times 10^4$	0.38—3.2	0.1—0.5
$Sr \times 10^{-6}$	100—400	161—333
$Ba \times 10^{-6}$	150—750	104—360
$U \times 10^{-6}$	0.2—1.9	0.3—0.7
$Th \times 10^{-6}$	0.53—5.4	0.58—1.96
$^{87}Sr/^{86}Sr$	0.704—0.712	0.703 6—0.704 8

a) Data from Carmichael et al., 1975. b) Statistics from 12 groups of data, the trace elements are measured with neutron activation analysis by the Institute of High-Energy Physics, Chinese Academy of Sciences.

volcanic activity is controlled by a faulted framework. The activity develops from the early Manketouebo Formation (J_{3-1}) acid volcanic breccia eruption, through the middle Manitu Formation (J_{3-2}) intermediate basic-intermediate acid volcanic lava overflow, to the Late Baiyingaolao Formation (J_{3-3}) acid pyroclastic rocks and tuff eruption. The eruption was powerful, with an explosive index E as high as 30—83 and the volcanic rocks accumulated as thick as 650—4600 m during 150—140 Ma B. P. In the intermittent period of the volcanic activity the intermontain fault basins received lake-river facies sediments. The Late Jurassic structure-geomorphologic landscape may be divided into three pairs of volcanic basement uplift and fault basins[9].

Silic-alkalic classification of the volcanic rocks indicates that most of them belong to trachytic rocks and potassic-volcanic rocks, with value of $Na_2O + K_2O$ increasing and SiO_2 (acidic-intermediate-acidic) changing with time and the eruption strong at both ends but weak in the middle of the period. Among the east, central, and west belts of volcanic rocks, the value of $Na_2O + K_2O$ (mainly content of potassium) and explosive index are the highest for the central one and roughly symmetric in the other two on both sides. The values of $Na_2O + K_2O$ are 8.06, 9.00, and 8.81, respectively, and the ratio of the explosive indices is 0.65 : 1.0 : 0.86, showing that the main crust segment of the Da Hinggan Mts. is the primary passage of the upwelling deep magma. The $^{87}Sr/^{86}Sr$ value, which marks the characteristics of the source region, is 0.704 8—0.707 7, mostly 0.705 1—0.705 5. Researchers have concluded that the intermediate acid magma originates from the lower crust, whereas the intermediate basic magma originates from the upper mantle[9]. The drastic volcanic eruption occurs prior to the rapid uplift of the Da Hinggan Mts., increasing the percolation of the upper lithosphere and preparing conditions for later thermal upwelling.

2.4 Large-scale intraplate anorogenic granite intrusion (J_3-K_1)

Plutonic rock intrusion began in this area in the Triassic, but happened in large scale in the Late Jurassic-Early Cretaceous. The magmatic activity of the plutonic rocks has the following features.

2.4.1 Pulsating character of the magmatic activity. The recent version of 1:50000 ultraunit geological mapping by Inner Mongolia Tenth Exploration and Exploitation Academy confirms the pulsating character of the Mesozoic magmatic activity in the Da Hinggan Mts. For example, the

Malerenba huge rock body of 300 km^2 in Baitazi area in the primary front belt is divided into three superunits: the dioritoid rock body (T_3), quartz monzonite (J_3), and granite-porphyry (K_1), each with a size ever larger and assuming an intrusive contact relation with the previous one as well as containing enclaves of earlier rock bodies. At intersections of the large faults with EW and NNE strikes, the pulsating rock bodies frequently appear as concentric ring structures, such as Posituo rock body, Xinlinzhen-Chaoyanggou rock body, and Baiyinnuo rock body, etc. ranging from southwest to northeast. The Xinlinzhen-Chaoyanggou rock body may be regarded as representative. The outer ring is Late Triassic gneissic granitite (213 Ma) with a wide contaminated belt between it and the surrounding Permian strata; the middle ring is Late Jurassic moyite (136 Ma) with tungsten mineralization phenomenon found in Chaoyanggou, and the plagioclase assumes anti-zonal structure in part of the granite on the inner side, indicating shallower invasion and faster cooling of the magma. And the center is Early Cretaceous porphyritic granite (127 Ma) with potassic phanerocrysts as large as 1 cm^2, part of which has become subvolcanic rock facies granite-porphyry or rhyolite. The Yuandanzishan rock body, which composes the summit at the center of the Chaoyanggou rock body, is actually an ancient volcanic neck and contains a large amount of irregular rock blocks from caved Permian hornfels. Those ring structures reflect the successive series of collection and release as well as the eventual centralized release of energy in the magma surge process, in which the volatiles are extremely active. It also can be seen that continuous supply of materials from the depth is available during the process.

2.4.2 Continuous rising of the interface of the magma emplacement. The activity of plutonic magma in the middle-south section of the Da Hinggan Mts. has experienced since the Late Triassic basic-ultrabasic-acid-alkalic process. Only the indexes reflecting magma evolution of the granite are sufficient to demonstrate the continuous rising of the magma emplacement interface in the process. They are: 1) Potassium content in granite is usually considered as an index of the magma contamination with the continental crust. K_2O/Na_2O value of granite in this area varies with time (T_3-J_3-K_1) at 0.22—0.38—0.76, reflecting the emplace interfacing interface rising from the closed system to the relatively open system. 2) The later period granite consists largely of porphyry with a phenocryst/matrix = 0.43, whereas the plagioclase phenocryst is mostly the low-temperature albite and the potash feldspar phanerocryst is low-temperature perthite, showing that the granite emplacement depth is small. 3) It can be seen from the progressive increase of the ΣREE and the variation of the REE distribution pattern (from the earlier smooth right decline to the later obvious Eu anomaly: δEu 0.26) that the magma crystallization depth tends to be shallower significantly. 4) The regional pressure data show that in the Late Jurassic the granite pressure is 2.16 MPa according to biotite-hornblende geobarometer and the Early Cretaceous granite pressure is 1.6 MPa, also reflecting the magma emplacing interface rising to lower pressure. 5) If the granite is broadly divided into two periods, then the early period (T_3-J_2) granite has a K_2O/Na_2O value of 0.55—1 and Rb/Sr value of 0.35—0.47 while the later period (J_3-K_1) granite has values of 1.2—1.7 and 0.98—1.93 respectively, also demonstrating the later magmatic intrusive depth getting shallower for the melted crust sourcse material to increase.

2.4.3 Anatectic origin of the magma. As mentioned above, the magma activity interface in this area continuously rises with time, forming successively plutonic, hypabyssal, ultra hypabyssal intrusive mass, subvolcanic rock, and volcanic rocks, but all of them originate from a uniform deep magma chamber. Various geochemical data have shown their anatectic origin but also revealed addition of continental crust materials in the upwelling process. For convenience, the above-mentioned magma is referred to as primary or anatectic magma to be differentiated from the autochthonous remobilized or migmatized magma. The most important feature of the anatectic granite is that it is controlled by structure. Its most part is composite annular shape massifs with pulsating character. The Late Mesozoic granite in this area is mostly moyite composed of granodiorite, quartz orthoclase, moyite, monzonitic granite, alkalic riebeckite granite with frequent granitic textures, graphic textures, and miarolitic textures. The rocks are rich in alkaline and silicon and poor in calcium, with $A/CNK<1$, $K_2O>Na_2O$, high ΣREE ($140—320\times10^{-6}$), rich LREE, and obvious Eu depletion (δEu 0.02 − 0.78), and are characterized by containing accessory mineral fluorite and apatite as well as cassiterite mineralization. R_1-R_2 projection fall into nonorogenic granite, and part of them belong to A_1 type granite according to the Rb/Nb-Y/Nb diagram[10]. The anatectic origin of the magma can be seen from the following.

1) Isotopic data. Preliminary statistics show that the representative Mesozoic granites in this area have values of $^{87}Sr/^{86}Sr$ as: T_3 0.704 9, J_2 0.707 5—0.708 0, J_3 0.704 2—0.704 8, K_1 0.704 9—0.708 7 (table 1), and the granites of a few mine field containing Sn, W, and Ag have higher initial Sr value. The Late Jurassic primary magma comes from the lower crust-upper mantle, and the Early Cretaceous magma bears increased fusion crust-materials. The $\varepsilon_{Nd}(t)$ value of the Mesozoic granite in this area is mostly concentrated within the range of 1—4, meanwhile the granites of different stages in this area, including the Late Jurassic volcanic rocks, show features of low or null oxygen isotopes[11]. The characteristics of $\varepsilon_{Nd}(t)$ and oxygen isotopes will be discussed elsewhere.

2) Volatile components. The volatiles contents in granite of this area are relatively high(F is averaged at 800×10^{-6} and may be as high as $1000—3000\times10^{-6}$, Cl averaged 240×10^{-6}, and S, P, and As all high), in which F and As are obviously abnormal. The arsenic-cobalt mineral deposit in Tongxing of Linxi County is formed in the Late Jurassic volcanic rocks. Most of the accessary minerals in the granite contain fluorite, apatite, zircon, and rutite, with the fluorite content increasing with time. Fluids are active in diagenesis with obvious potash alteration, albitization, flupritization, silicatization, and similar phenomena. It is noticeable that there exist several typical uranium mineral deposits of sodium-metasomatic type, including Hongshan and Guangxing uranium deposits, where Na_2O is as high as 9% with the highest up to 11% and it is the sodium metasomatism that causes so high uranium concentration. And Du[12] claims that such an alkali metasomatism is actually mantle metasomatism.

Accompanying the late-period Early Cretaceous alkaline (120—100 Ma B.P.) granite emplacement, there occurs basic dike swarm intrusion and alkaline basalt overflow. And basalt is widely distributed in fault basin on both sides of Da Hinggan Mts. In the basalt, total alkali is 5.58%—8.83%, Na/K 1.1—3.5, TiO_2 2%—3%, Ti/V 76—79 values, showing a deep source of the basalt.

Summary of all the aforementioned facts leads to the idea that the Late Mesozoic granite in this area belongs to subalkalic-alkalic nonorogenic granite formed in an intraplate extension environment. And the Rb/Nb-Y/Nb incompatible element analysis reveals that some of the granites also possess features of A1-type granite, which is considered as a product of intraplate rift, mantle plume, or hot spot activity[10].

3 Discussion on mechanisms of thermal evolution

The drastic magmatic activity in the middle-south section of the Da Hinggan Mts. is mainly concentrated in the period of 150—120 Ma B. P., the volcanic activity in 150—140 Ma B. P., and the granite emplacement in 140—120 Ma B. P. (late J_3-K_1). The magma from volcanic eruption does not occupy much room in the crust, yet the granite emplacement after volcanic activities would occupy a rather larger room in the upper crust, hence more representative of the strength of the crust extension. The Late Mesozoic granite takes up about 10%—15% of the whole area, which may represent the proportion of the crust extension. The time-related variation of the Mesozoic granite in this area from the typhonic plutonic rocks to typhonic hypabyssal ones indicates continuous mantle source material supply from the deep magma chamber during the 20 million a. Of course, the upwelling magma has changed its composition because of the continuous addition of crust-source materials, but given the entire magma evolution tendency it is difficult to be explained with a viewpoint of magmatic differentiation. It can be seen from comparison between the Early Cretaceous overflowed alkalic dorgalite with continental rift properties ($^{87}Sr/^{86}Sr$ 0.7047)and the Late Jurassic erupted trachytic volcanic rocks and comparison between the Early Cretaceous alkalic granite rich in REE deposit and the previous subalkaline granite that the magma origin has a sustained deepening tendency, which in turn indicates that the lithosphere is in an extension state in the entire process with the tension strength varying intermittently. The dike swarm intrusion ($J_{1\text{-}2}$, K_1) and large-scale granite emplacement (the end of J_3-K_1) are important expressions of the lithosphere extension, and the strongest extension occurs in the Early Cretaceous, which is just the period of rapid uprising of the Da Hinggan Mts., symmetric fault depression of the Erlian and Songliao basins on both sides, and formation of the Ganzhuermiao and Kalaqinqi metamorphic core complex[13]. The entire Mesozoic magma evolution process, from the Early Mesozoic remobilization and metamorphism produced by underplating throught emplacement of the basic magma carrying mantle source enclaves and the Early-Middle Jurassic basic dike swarms expansion to the Late Mesozoic extensional orogeny of the Da Hinggan Mts., reveals an important fact: during the long 100 Ma, it is the mantle-upwarping-caused lithosphere extension and thinning rather than the mechanical stretching that produces the deep source magma upwelling. It is only the power coming from the depth of the lithosphere that makes continuous magma supply and emplacing interface rising realized. Thus the mantle plume theory should be the best option for revealing such a power source.

The Mesozoic mantle upwarping features of the Da Hinggan Mts. have continued until the Cenozoic. In this area, especially on both sides of the Da Hinggan Mts., large area eruptions of basalt-bearing mantle source enclaves occur. A recent geophysical section across the orogene reveals an obviously thinned lithosphere of 70 km underneath the orogene compared to 110 km of the platform and a clear low resistivity zone under the main peak, which is supposed to be an aesthenosphere upwelling area[14].

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