The late Paleoproterozoic extension event: aulacogens and dyke Swarms in the North China craton*

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Received June 24, 2005

Abstract The extension structures and tectonic implication in the North China Craton (NCC) are discussed in this paper based on the mafic dyke swarms and geochronology, combining with the geochronology of aulacogens. The late Paleoproterozoic time is the important turning point in the Precambrian evolution of the NCC. The extension system (e.g. aulacogens and dyke swarms) is widespread in the NCC, which marks the carbonization of the NCC with the rigid characteristic similar to the modern plate. The paleostress field modeling suggests that the dyke swarms and aulacogens are arogenic extension marking the start of the supercontinent, not synorogenic and post-orogenic extension. The mafic dyke swarms in the NCC mainly ranged from 1.83 to 1.77 Ga. The extension of the NCC is very limited brittle extension, the average extension ratio is only 0.35% given by mafic dyke swarms extension calculation, so most of extension in the NCC is contributed by the aulacogens. The mafic dyke swarms are related with the aulacogens in the origin.

Keywords: **North China craton, late Paleoproterozoic, aulacogens, mafic dyke swarms, extension.**

In recent years, the Precambrian tectonic division and evolution of the North China craton (NCC) have been studied in progress, for example, it is accepted that the NCC is divided into the Eastern Block, the Western Block and the Central Zone, though the collision time is controversial[1—3]. Zhao et al. suggested that the NCC was united along the Central Orogen Zone by the collision between the West Block and the East Block at 1.85 Ga, then finished the carbonization. Kusky and Li suggested that two Archaean blocks collided and formed the Central Orogen Zone at ~2.5 Ga and were involved in the Paleoproterozoic evolution as a uniform block, and 1.90—1.85 Ga high pressure granulite and retrograde eclogite in the northern Central Zone and along the northern margin of the NCC resulted from the late Paleoproterozoic Andes-type orogen event (Inner Mongolian-North Hebei Orogen) and the crustal uplift[1—5]. It is convinced that the Precambrian NCC underwent the last orogen and metamorphism event which carbonized the whole craton though the exact location of the late Paleoproterozoic orogen is very controversial[5]. The late Paleoproterozoic is the turning point in the Precambrian evolution of the NCC which developed extensive mafic dyke swarms similar to other cratons in the world. The mafic dyke swarms are a type of extension structures emplacing the pre-existing fracture system to form the tectonic magmatism usually induced in the early rifting[6]. The further study on the extension event and origin of the dyke swarms and aulacogens is helpful to constrain the tectonic evolution of the NCC and the reconstruction of the paleocontinent.

Some precise ages gained in the recent years provide the geochronological constraint on the late Paleoproterozoic extension event of the NCC. The late Paleoproterozoic extension and tectonic implication at the turning point of the Precambrian evolution of the NCC are discussed based on the extension structures, geochronology and stress field of the mafic dyke swarms and aulacogens in this paper.

1 The late Paleoproterozoic aulacogens of the NCC

The net-like aulacogens were developed in the NCC in the late Paleoproterozoic. The NE-trending aulacogens in the southern NCC stretched into the interior of the NCC and the E-W trending aulacogens are distributed along the northern margin of the NCC. At least five late Paleoproterozoic aulacogens have been identified, including Yanliao aulacogen, Xiong' er-Zhongtiao aulacogen, Baiyunebo-Zaertai aulacogen, Helanshan aulacogen and Jinshan aulaco-

* Supported by National Natural Science Foundation of China (Grant Nos. 40172066 and 40314141)
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gen[7]. Among them, Yanliao aulacogen and Xiong'er-Zhongtiao aulacogen with the characteristics of the triple junction stretching into the interior of the NCC and intersecting adjacent to Shijiazhuang play the important role in the late Proterozoic evolution of the NCC (Fig. 1).

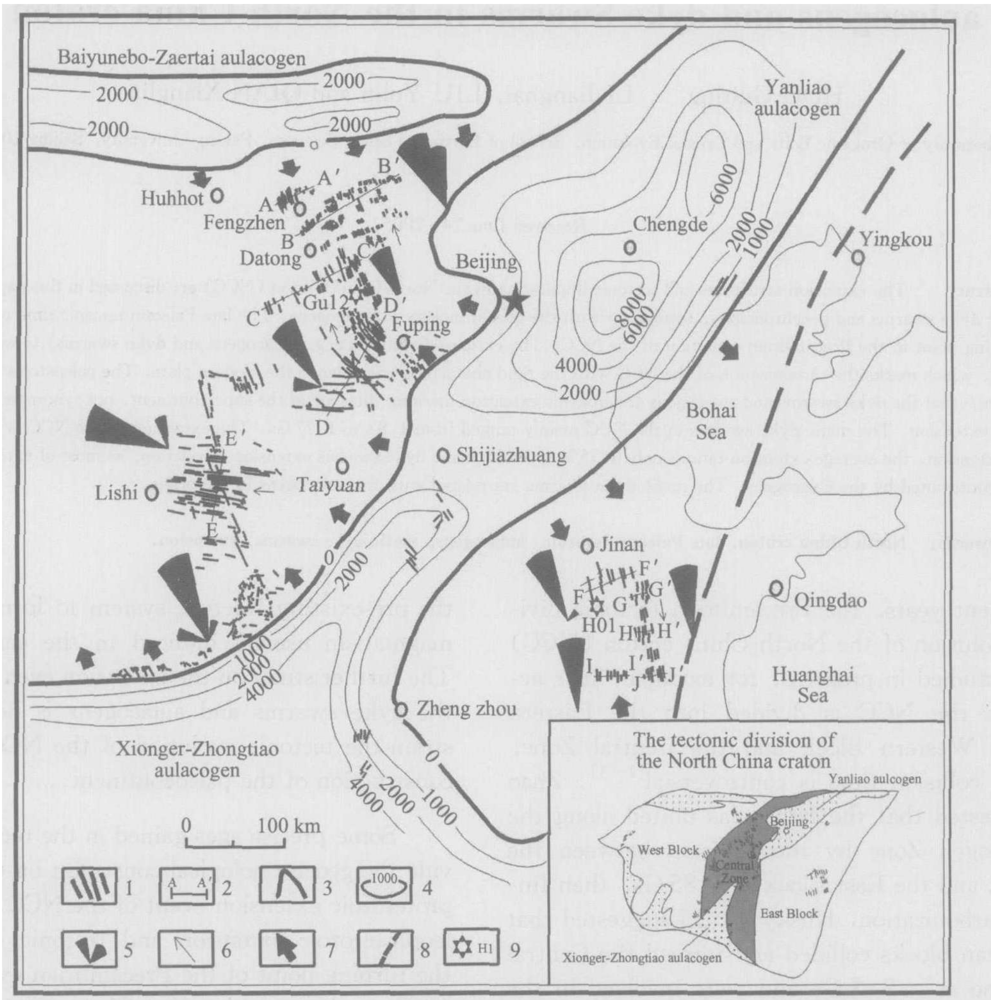

Fig. 1. The spatial relationship between the Proterozoic aulacogens and mafic dyke swarms in the NCC (dyke swarms source: 1:50000 and 1:200000 geological maps, the sedimentary isopatch after He[8]). 1, dyke swarms; 2, survey lines; 3, boundary of aulacogen; 4, sedimentary isopatch of aulacogens; 5, roses diagram of dykes; 6, emplacement direction; 7, extension direction; 8, Tanlu Fault zone; 9, sample location.

The older ages of volcanic rocks and sedimentary rocks in these aulacogens help us to know the early extension of the NCC. The NNE-trending Xiong'er-Zhongtiao aulacogen develops the volcanics rocks (Xiong'er Group or Xiyanghe Group) in the junction area of Jin-Yu-Shaan stretching into the interior of the NCC (Fig. 1). The mafic dyke swarms widespread along the margins of the aulacogen and pendicular to its two margins suggest the mafic dyke swarms are related with the aulacogen. The andesite rocks from the Xiong'er Group in the Xiong'er-Zhongtiao aulacogen gave the U-Pb SHRIMP age of 1840 ± 28 Ma, and the age of 1.83 Ga averaged by 39 ages of volcanic rocks in the Xiong'er Group is suggested as the time of the triple junction rift system[9]. The magmatism in the Xiong'er-Zhongtiao aulacogen may be earlier based on the zircon U-Pb age of 1959 ± 44 Ma gained from the rhyolite porphyry (Xiong'er Group) in the Songshan, Henan[10].

Ren et al.[11] and Zhao et al.[10] gave the zircon U-Pb ages of 1761 ± 16 Ma from the pyroxene diorite (Xiong'er Group) and 1750 ± 65 Ma from the orthophyre (Majiahe Formation, Xiong'er Group) in Ruyang, Henan Province, which possibly indicates the upper age of Xiong'er-Zhongtiao aulacogen.

In conclusion, the Xiong'er-Zhongtiao aulacogen might be active from 1.95 to 1.75 Ga, and the triple junction rift was formed at 1.83 Ga.

The Yanliao aulacogen was also a triple junction rift stretching into the interior of the NCC (Fig. 1). The volcanics-sediments (Changcheng Series and Jixian Series) were deposited in the aulacogen mainly distributed in the Yanshan-western Liao, Zhangjiakou-Xuanhua and the southern Taihang. The shale and siltstone in the Changzhougou Formation in the Jixian section has yielded the Pb-Pb age of 1848 ± 57 Ma as the early depression age of the aulacogen[12]. Other anorogenic intrusion (e. g. rapakivi granite, anorthosite, gabbro and granite) also developed in the aulacogen. For example, in Hebei Province, the K-felspar quartz vein at Zhangjiakou has yielded the U-Pb age of 1826 ± 31 Ma[13], the grabb-anorthosite at Damiao has yielded a Sm-Nd whole rock isochron of 1735 ± 39 Ma[14] and rapakivi granite at Damiao has yielded a U-Pb whole rock isochron age of 1683 ± 4 Ma[15].

The volcanic flow in the Tuanshanzi and Dahongyu Formations has yielded the single zircon U-Pb ages of 1683 ± 67 Ma and 1625 ± 6 Ma[16,17].

In conclusion, the Yanliao aulacogen depressed and developed the plutons in the early rifting and volcanic activity in the middle and late rifting.

The K-riched trachyte in the upper Dongjianzhuishan Formation (Baiyunebo Group) has yielded the single zircon U-Pb age of 1728 ± 5 Ma which indicates that the Baiyunebo-Zaertai aulacogen might begin at 1.8 Ga[18]. The Helanshan and Jinshan aulacogens were also developed in the late Paleoproterozoic[7].

2 The late Paleoproterozoic mafic dyke swarms in the NCC

The dyke swarms are developed in the Archaean crystal basements among five aulacogens in the late Paleoproterozoic, which mostly are mafic dyke swarms, few are acidic. The late Paleoproterozoic mafic dyke swarms are the largest dyke swarms in the NCC as the extension structures induced from the rifting are commonly distributed adjacent to the rift or among the rift system. The mafic dyke swarms in the NCC are mostly distributed along the west of the Yanliao aulacogen and Xiong'er-Zhongtiao aulacogen, and a few on the east of two aulacogens, for example, Datong-Fengzhen area, Hengshan area, Luliang area, Fuping area, Zhongtiao area and western Shandong (Fig. 1)[19—22].

About 640 mafic dykes with the width >5 m are developed in the NCC and their average width is 10 m. These mafic dyke swarms are undeformed, unmetamorphosed and vertical. The diabase is the dominant dyke, few are gabbro-diabase or diabase-porphyrite. The mafic dyke swarms have both alkali and tholeiitic basalt compositions. They are of within-plate anorogenic magmatisms in the continental rift system setting similar to the Yanliao and Xiong'er-Zhongtiao aulacongens[22,23]. The dominant orientation of the mafic dyke swarms is NNW, a few are NW or SN trends, few are E-W and NE based on the rose diagram analysis (Fig. 1). The mafic dyke swarms in Jin-Ji-Meng, Hengshan and Taihang area trend 330°—340° pendicular to the western margin of Yanliao aulacogen. The branching northwestward and flow evidence along the chilled margins of the dyke swarms indicate that the dyke swarms were emplaced northwestward from the Yanliao aulacogen[24]. The dyke swarms in the Luliangshan are developed on the west of junction between Yanliao and Xiong'er-Zhongtiao aulacogens, of which the dominant orientation is 275°—285°, and a few trend 320°—330°. These branching westward and flow evidence indicate that the dyke swarms were emplaced westward from the junction of two aulacogen[24]. The mafic dyke swarms orientation is also pendicular to the western margin of Xiong'er-Zhongtaio aulacogen, of which the branching northwestward indicates that the mafic dyke swarms were emplaced northwestward induced by the rifting. The mafic dyke swarms in the western Shandong trend 320°—340° in the northern area and 340°—360° in the southern area, of which the branching southward and flow evidence indicate that the mafic dyke swarms were emplaced southward from the Yanliao aulacogen[25].

Based on the analysis above, the mafic dyke swarms are related to the aulacogens, maybe they are formed in the same extensional episode.

2.1 The ages of dyke swarms

The undeformed and unmetamorphosed mafic dyke swarms provide the geochronological constraint on the Precambrian evolution of the NCC. The mafic dyke swarms cut all Archaean host units, but are covered by the Meso-Neoproterozoic layers along the western margin of Yanliao and Xiong'er-Zhongtaio aulacogens. The evidence suggests that the mafic dyke swarms were emplaced in the Paleoproterozoic or early Mesoproterozoic.

In recent years, the precise dating of zircons from mafic dyke swarms provides reasonable constraint on the geochronology of the mafic dyke swarms in the NCC. The mafic dyke swarms on the west of Yanliao aulacogens have yielded the U-Pb ages. Peng et al.[23] reported the SHRIMP U-Pb age of 1778 ± 3 Ma. Li and Hou[26] reported a single zircons U-Pb age of 1769.1 ± 2.5 Ma for a NNW-trending mafic dyke in Hengshan area, where sample GU12 was collected (Fig. 1). Liao et al. gave the ^{39}Ar-^{40}Ar age of 1780.7 ± 0.5 Ma for the mafic dykes in the southern Taihangshan. These reasonable ages indicate that the mafic dyke swarms were emplaced at 1.8 Ga on the west of aulacogens. The mafic dyke swarms are extensive tectonic magma event in the late Paleoproterozoic.

Did the mafic dyke swarms on the east of two aulacogens intrude with the mafic dyke swarms on the west of the aulacogens in the same episode? The precise dating of mafic dyke swarms in the eastern NCC is the key to answer this question.

The mafic dyke swarms in the eastern NCC are mainly distributed in the western Shandong Province. A large NNW-trending diabase-porphyrite was found at Hongmen in the Taishan area where a sample H1 was picked for the dating of the dyke (Fig. 1). The U-Pb SHRIMP dating was measured on the SHRIMP II in the center of Beijing SHRIMP. Two types of zircons with two groups of ages were identified by the isotopic analysis (Table 1)[1)]. Type 1 zircons are of irregular shape, anhedral crystals with cracks and not well preserved. Type 2 zircons are equant or euhedral crystals with few cracks and well preserved in shape. Type 1 have high Th/U ratios (generally > 1.0, most > 0.5); Type 2 zircons have lower Th/U ratio of 0.1—1.0 (most > 1.0) (Table 1). In contrast, the Cathodoluminescence (CL) image of type 2 zircons is lighter than that of type 1 zircons (Fig. 2 (a)). Two types of zircons develop the oscillatory zoning (Fig.2 (b), (c), (d)), suggesting they are magmatic origin, but from different magmatism in the different episodes.

Table 1. The U-Pb SHRIMP isotopic analysis results for sample H1 from the dyke at Taishan

Spots	Zircon type	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	f_{206} (%)	$^{207}Pb^*/^{206}Pb^*$	SD (10^{-2})	$^{207}Pb^*/^{235}U$	SD (10^{-2})	$^{206}Pb^*/^{238}U$	SD (10^{-2})	$^{206}Pb/^{238}U$ age (Ma)		$^{207}Pb/^{206}Pb$ age (Ma)	
H1-1	I	135	198	1.51	53.3	0.29	0.1657	0.72	10.43	2.6	0.456	2.5	2400	±64	2515	±12
H1-2.1	II	438	267	0.63	123	0.07	0.1128	0.49	5.07	2.5	0.326	2.5	1818	±44	1844	±9
H1-2.2	II	363	184	0.52	97.6	0.15	0.1121	0.71	4.84	2.6	0.313	2.5	1746	±42	1834	±13
H1-3	I	164	213	1.34	61.3	1.96	0.1679	2.0	9.81	3.4	0.424	2.7	2225	±61	2538	±34
H1-4	I	90	95	1.08	34.4	3.61	0.1695	2.1	9.89	3.6	0.423	3.0	2227	±68	2554	±34
H1-5	I	127	156	1.26	45.9	1.04	0.1623	0.98	9.26	2.7	0.414	2.5	2182	±56	2479	±16
H1-6	I	137	181	1.37	48.5	1.19	0.1634	1.0	9.14	2.7	0.406	2.5	2136	±55	2491	±17
H1-7	I	378	193	0.53	89.6	3.10	0.1646	1.6	6.05	4.0	0.266	3.6	1408	±49	2506	±26
H1-8	I	87	107	1.27	34.9	0.14	0.1651	0.94	10.60	2.8	0.466	2.6	2452	±69	2508	±16
H1-9.1	II	517	55	0.11	51.8	0.12	0.1106	1.1	1.776	2.9	0.117	2.7	670	±18	1809	±19
H1-9.2	II	1456	1556	1.10	385	0.03	0.1110	0.52	4.71	2.5	0.308	2.5	1719	±41	1815	±9
H1-10	II	1291	67	0.05	288	0.02	0.1065	0.39	3.81	2.5	0.260	2.5	1466	±35	1741	±7
H1-12	II	853	646	0.78	228	0.07	0.1151	0.85	4.93	2.6	0.311	2.5	1728	±42	1882	±15
H1-13	I	53	59	1.15	20.2	0.49	0.1727	1.3	10.52	3.0	0.442	2.7	2302	±65	2584	±21
H1-14	I	243	311	1.32	90.3	0.17	0.1648	0.60	9.80	2.6	0.431	2.5	2265	±59	2505	±10
H1-15	I	226	168	0.77	81.3	0.32	0.1696	0.65	9.76	2.6	0.417	2.6	2179	±56	2554	±11
H1-16	I	277	333	1.24	106	0.13	0.1643	0.50	10.04	2.6	0.443	2.5	2332	±60	2500	±9
H1-17	I	881	204	0.24	143	0.43	0.1338	0.68	3.48	2.6	0.189	2.5	1042	±25	2148	±12
H1-18	I	197	112	0.59	72.4	0.23	0.1716	0.69	10.08	2.7	0.426	2.6	2218	±59	2574	±11
H1-19	II	1338	408	0.31	366	0.05	0.1129	0.40	4.95	2.5	0.318	2.5	1772	±43	1846	±7
H1-21	I	167	284	1.75	64.1	0.25	0.1677	0.75	10.29	2.7	0.445	2.6	2334	±62	2534	±13
H1-22	I	70	40	0.59	29.9	1.61	0.1663	2.0	11.24	3.4	0.490	2.8	2603	±79	2520	±33
H1-23	II	355	123	0.36	104	0.21	0.1111	0.70	5.20	2.7	0.339	2.6	1893	±48	1817	±13
H1-24	I	717	55	0.08	91.6	0.80	0.1400	0.94	2.85	2.7	0.1475	2.5	813	±20	2228	±16
H1-25	I	395	67	0.18	84.5	4.99	0.1532	2.0	4.98	3.1	0.236	2.5	1268	±30	2384	±32

* represent radiogenic, f_{206}(%) is the percentage of common ^{206}Pb in total lead, U, Th and Pb were measured in Beijing SHRIMP II Center.

1) Hou G.T., Liu Y.L., Li J.H. et al. The U-Pb SHRIMP dating of mafic dyke swarms at Mt.Taishan. Journal of Asian Earth Science (in Press).

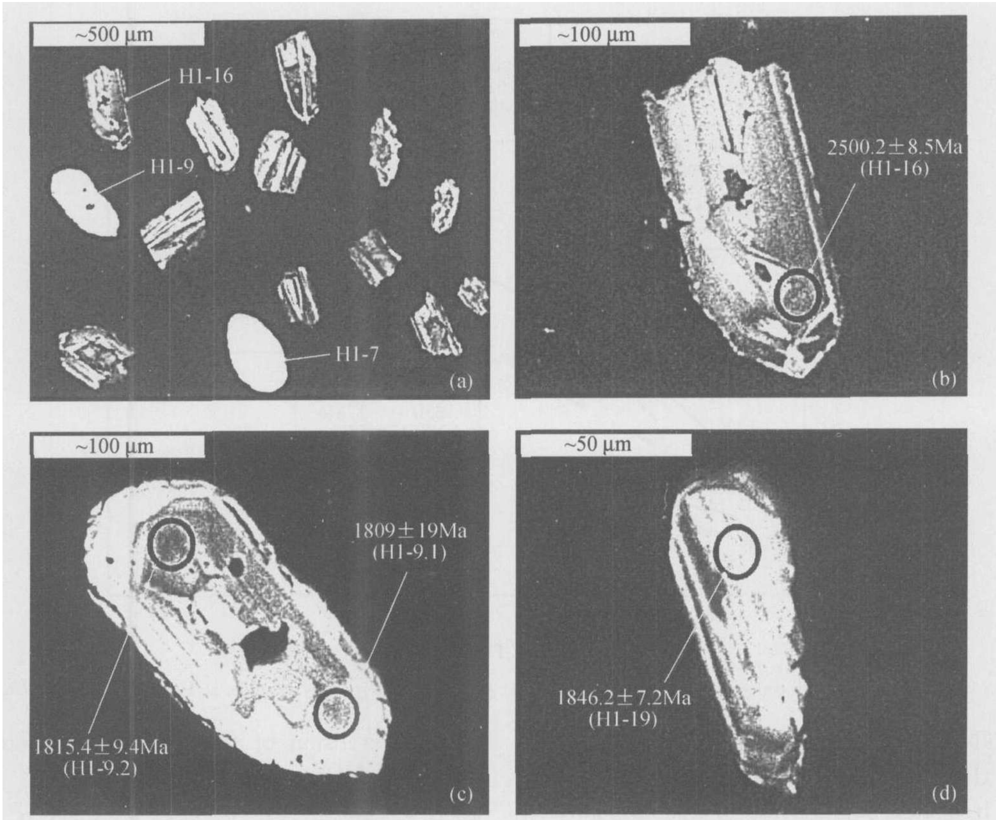

Fig. 2. The CL images of sample H1 picked from the diabase-porphyrite dyke at Hongmen in the Taishan area.

The U-Pb concordant diagram based on the isotopic analysis of 24 zircons has been yielded (Fig. 2). Type 1 zircons (18 zircons, 18 spots) give the $^{206}Pb/^{238}U$ ages from 457 Ma to 2603 Ma, among which 13 zircons are near the concordant line giving an upper intercept age of 2544 ± 24 Ma (MSWD = 8.5) and define a weighted mean $^{207}Pb/^{206}Pb$ age of 2523 ± 18 Ma (MSWD = 4.6) (the others are far away from the line due to the loss of radiogenic lead). These ages suggest that type 1 zircons are late Neoarchean, about 2.52 Ga old (Fig. 3). Type 2 zircons (6 zircons, 8 spots) give the upper intercept age of 1830 ± 17 Ma (MSWD = 1.4) and define a weighted mean $^{207}Pb/^{206}Pb$ age of 1837 ± 18 Ma (MSWD = 3.4). These ages suggest that type 2 zicons are 1.83 Ga old (Fig.3).

The host rock of the large dyke is the Neoarchaeon Dazhongqiao tonalite with the U-Pb disconcordant age of 2555 ± 5 Ma[28], close to the age of type 1 zircons. This suggests that type 1 zircons were entrapped from the host rock of the dyke. Type 2 zircons are interpreted to be primary crystallization products of the dyke magma and therefore date the time of dyke emplacement in Taishan area at 1830 ± 17 Ma supported by the field evidence. The ages of mafic dyke swarms in the eastern NCC and the western NCC are consistent with those of Yanliao and Xiong'er-Zhongtiao aulacogens. These ages suggest that the mafic dyke swarms on the west and east of aulacogens in the NCC were emplaced at ~1.8 Ga.

The E-W trending dyke swarms in the Lüliang area are later than the NNW-trending dyke swarms cut by the E-W trending dykes due to the junction of two aulacogens at Taiyuan and Zuoquan[29].

In conclusion, during the late Paleoproterozoic (1.83—1.77 Ga), the widespread extension events happened throughout the whole NCC marked by the mafic dyke swarms and aulacogens.

2.2 The extension stress field of the dyke swarms

The mafic dyke swarms are intrusions that were formed by mafic magma intruding into the pre-existing fracture system and cooled very quickly. The pattern of dyke swarms and the shape of single dyke are controlled by the mechanics of the pre-existing fractures, so the dyke swarms can indicate the mechanism of the pre-existing fractures. In general, the dyke swarms with the tensional shape follow their trends parallel to the regionally applied compressive stress while their trends are perpendicular to the extension direction.

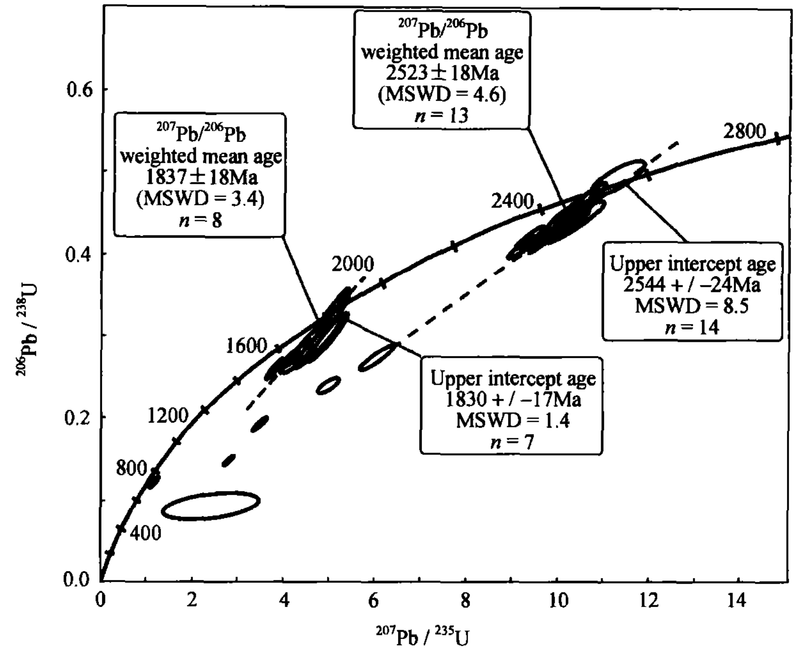

Fig. 3. The SHRIMP U-Pb concordant diagram of sample H1 for the diabase-porphyrite dyke at Hongmen in the Taishan area.

Most NNW-trending mafic dyke swarms were emplaced in the tensional pre-existing fractures with vertical and irregular boundaries, which are parallel and stable. These characteristics suggest that the pre-existing fracture system in which the mafic dyke swarms were emplaced was formed in the regional extension stress field. The dyke swarms are regarded as a typical extension marker. The crustal extension in the North China craton can be calculated based on the width statistics of dyke swarms on ten survey lines (Fig. 1). The formula $\lambda = \sum d_i/(L - \sum d_i)$ is employed in the calculation, where λ is the extension ratio; $\sum d_i$ is the total width of dykes on the survey line; L is the length of survey line. The local extension ratios calculated are presented in Table 2.

The extension ratios in northern Datong-Fengzhen-Fuping areas along the Yanliao aulacogen range from 0.35% to 0.48%, bigger than that in the southern Datong-Luliang-northern Taishan areas of 0.14%—0.28% due to near the terminal of aulacogens or far from the aulacogen. The south of western Shandong has a relatively big extension ratio of 0.3%—0.5% due to close to the Yanlu Fault. The average crustal extension ratio of the NCC is 0.35% contributed by the mafic dyke swarms. The very little extension suggests that the mafic dyke swarms represent the very limited elastic fractures as "Upper Crustal Joint System" induced by the big extension of the late Paleoproterozoic aulacogens in the NCC. Most extension of the late Paleoproterozoic NCC is contributed by the aulacogens system.

Table 2. Calculation results of extension ratio on the late Paleoproterozoic mafic dyke swarms in the NCC

Survey lines	Length of line (m)	Total width of dykes (m)	Extension ratio (%)	Area	Dominant orientation of dyke swarms
AA′	48000	230	0.48	Datong	NNW
BB′	110000	490	0.45	Datong	NNW
CC′	11000	270	0.25	Hengshan	NNW
DD′	80000	280	0.35	Fuping	NW
EE′	60000	220	0.28	Western Taiyuan	E-W
FF′	50000	70	0.14	Taishan	NNW
GG′	20000	80	0.4	Taishan	NNW
HH′	20000	60	0.3	Mengyin	NNW
II′	30000	90	0.3	Linyi	SN
JJ′	20000	100	0.5	Linyin	SN
Average extension			0.35	NCC	

The dyke swarms orientation can be regarded as observed paleostress indicators to show the horizontal principle stress orientation. The late Paleoproterozoic stress field of the NCC can be reconstructed by finite element models based on the rigid crustal characteristic of the NCC[30]. The constraints on the model are the extension of two triple junction aulacogens at the southern and northern NCC and limited the eastern boundary by Tanlu Fault. The orientation of the tectonic paleostress in the NCC was predicted using a two-dimensional elastic finite element analysis software SAP5. The stress pattern in the vector plot of maximum nodal principle stress is given in Fig. 4.

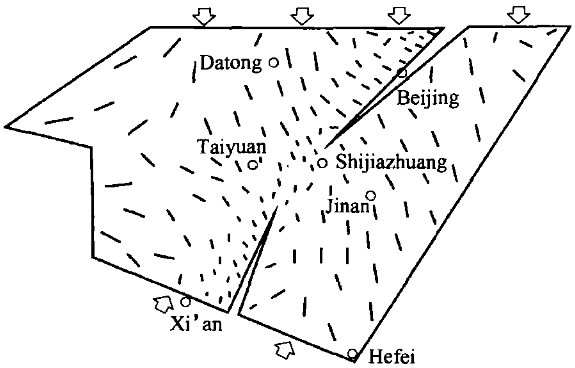

Fig. 4. Paleostress pattern in the vector plot of maximum nodal principal stress (σ_{Hmax}) for the late Paleoproterozoic North China Craton[30].

The reasonable modeling results of paleostress field rely on the qualitative fit between predicted and observed stresses. The stress field pattern modeled by SAP5 showed that the maxium principle stress vectors are most consistent with the dyke swarms orientations shown in Fig. 4. The maxium principle stress vectors are NNW-trending in Shijiazhuang-Datong areas, WNW-trending in the western Taiyuan, NW-trending in Shijiazhuang-Xian area, NNW-trending and SN-trending in the western Shandong, very consistent with the dyke swarms roses diagram in Fig. 1. These σ_{Hmax} orientations in the stress vector plot fit well to the mafic dyke swarms trends throughout the NCC. The small extension ratio and principle stress pattern indicate that the pre-existing fractures are crustal "Joint Swarms" and the dyke swarms in both the eastern and western craton are induced by the extension of the Yanliao and Xiong' er-Zhongtiao aulacogens in the same extension stress field setting (Fig. 1).

3 Conclusions

The North China craton was united and carbonized at 1.85 Ga in the late Paleoproterozoic after the last Precambrian orogen and metamorphism. After 1.85 Ga, the NCC developed an extensive extension. The Xiong'er-Zhongtiao aulacogen filled by the volcanics (Xiong'er Group or Xiyanghe Group) was developed and the triple junction formed at 1.83 Ga in the southern margin of NCC, and the Yanliao aulacogen in the northern NCC developed the plutons (1.8—1.7 Ga) in the early rifting and later developed the volcanics (Tuanshanzi Formation and Dahongyu Formation). The magmatism in the Yanliao aulacogen is anorogenic plutons not as volcanics in the Xiong'er-Zhongtiao aulacogen, e.g. rapakivi. The mafic dyke swarms are related with the volcanic rocks in the aulacogens supported by the evidence of flow structures and geochemistry[22,23,31]. The NCC developed the widespread mafic dyke swarms across the western block, the central zone and the eastern block of the craton from 1.83—1.77 Ga, and most mafic dyke swarms were emplaced at 1.80 Ga. The extension ratio of mafic dyke swarms indicates that the extension is only very limited brittle one, the average extension ratio is 0.35%. Most extension of the NCC was contributed by the extension of aulacogen.

Based on the analysis of the precise dating, the mafic dyke swarms in the western Shandong and Shanxi are the same extension episode from 1.83—1.77 Ga, about 1.80 Ga (±0.03 Ga). The last Precambrian orogen happened from 1.90 to 1.85 Ga, so the mafic dyke swarms are not synorogenic extension, which are later than the orogen event in the time range. The mafic dyke swarms orientations perpendicular to the late Paleoproterozoic orogen are not parallel the orogen, so the mafic dyke swarms are not post-orogenic extension. The aulacogens and dyke swarms across all Neoarchaean and early Paleoproterozoic units are the same extension in the same tectonic stress field related with the extension of aulacogens and the compression from the southern and northern margins of the craton after the carbonization of the NCC.

In conclusion, according to the geochronology, distribution, geochemistry, flow structures[22—25] and tectonic stress field, the mafic dyke swarms and aulacogens are the same extension episode in the same mechanism, which can be compared with the mafic dyke swarms and aulacogens in other cratons in the world[32,33]. The mafic dyke swarms and aulacogens mark the starting of the late Paleoproterozoic NCC breakup as part of Pre-Rodinia supercontinent breakup.

Acknowledgement We are grateful to Prof. Henry C. Halls who went through and improved this paper, to Prof. Gordon S. Lister who gave us many helps, and to Prof. Jian Ping and an anonymous reviewer to review this paper, to Song Biao and Wang Yanbin who guided us to date the SHRIMP age.

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