Mechanism of the Mafic Dyke Swarms Emplacement in the Eastern Block of the North China Craton

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Keywords: mafic dyke swarms, flow structures, emplacement, Eastern Block

Abstract: Based on field investigation and microscopic study, the Late Paleoproterozoic mafic dyke swarms in the western Shandong, Eastern Block of the North China Craton (NCC) have been researched. These dykes have similar features with those in the northern Shanxi and Luliang areas of the NCC.

(1) Their strikes change gently from NS-trending or even NNE-trending in the southern part to NNW-trending in the northern part, and are vertical to the Yanliao-Zhongtiao aulacogen if eliminating the influence of the extension of Bohai Basin;

(2) The sequence stratigraphy and isotope dating indicate that their ages range from 1.83Ga to 1.71Ga in the Late Paleoproterozoic. These undeformed and unmetamorphic dykes are vertical and their compositions are typical diabase;

(3) The calculation results of extension ratio show that the average extension ratio of the crust at that time was 0.43%;

(4) The chilled margins of these dykes have reserved abundant flow structures which show the characteristics of the magma activity including the direction and way of the dyke emplacement. For example, the bottom of the dyke is not batholith or stock that shows the magma may not intrude vertically from below. Most of the dykes extend from NNW to SSE for hundreds of meters or even tens of kilometers, and their widths may diminish gradually and pinch out at last. There are some dyke branches in the southern segments of the dykes and intruded into the country rock along the dominant orientation. These features of the dykes indicate that the magma flowed from NNW to SSE.

There are also some flow structures in the contact zone between the dyke and the country rock, such as scour marks, mineral lineations, orientational xenoliths and so on, which are formed by the magma flow friction. The orientations of these marks were controlled by the laminar flow of the magma, and could reflect the direction of magma flow.

The flow of magma inside fractures is helpful for us to understand how continental dyke swarms developed. The research on the dyke swarms of the NCC indicate that the paleostress field offered the space for the magma and the flow structures and also indicate the magma intruded subhorizontally from the aulacogen to the pre-existing fractures.

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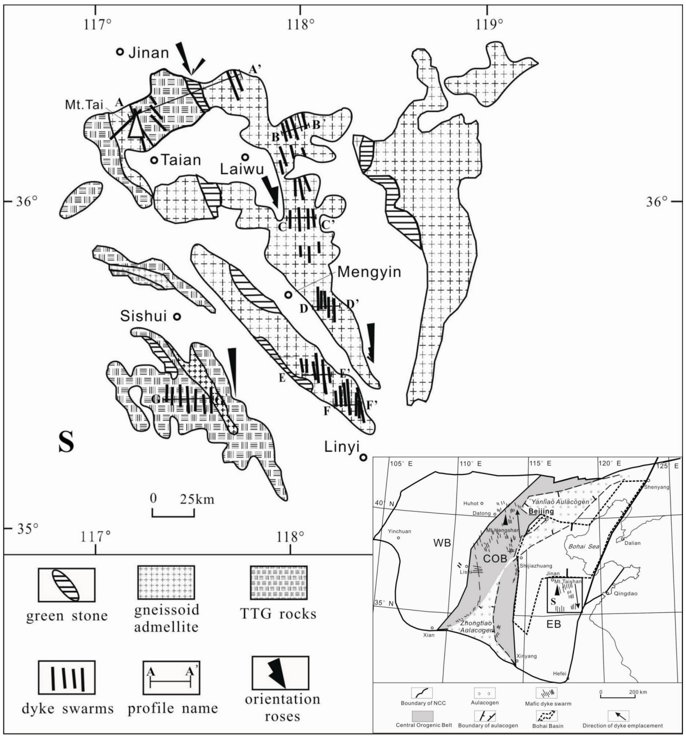
Introduction

In recent years there has been growing interest in the investigation of dyke emplacement processes, not only because dykes represent former conduits of magma from deeper levels of the Earth to the surface but also because dyke swarms give information about tectonic processes that deformed the lithosphere (Hou, *et al.*, 2005). The flow of magma inside fractures is one issue of basic importance in understanding how continental swarms developed (Raposo, 1995). Magma flow directions are traditionally investigated by petrographic fabric, oriented vesicles and fingers, grooves or lineations.

Figure 1. Geological map of Western Shandong



Geological map of Western Shandong, EB of the NCC (compiled from Hou *et al.*, 2005). Insets show the distribution of the Precambrian mafic dyke swarms of the NCC (compiled from Hou *et al.*, 2006a)

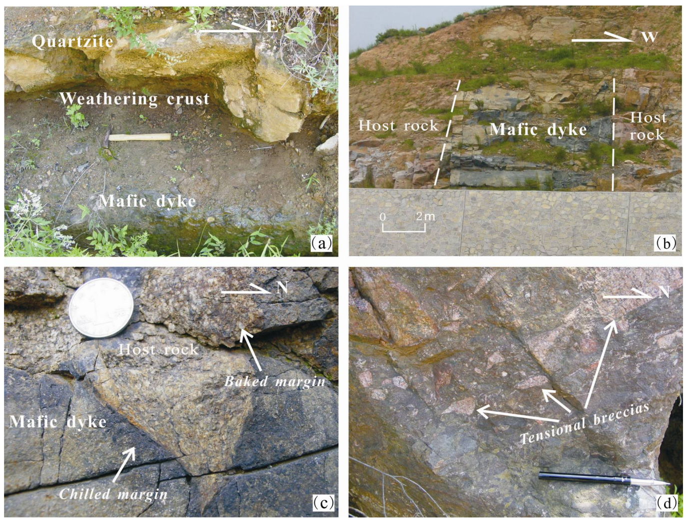
As the other main cratons on earth, Precambrian mafic dyke swarms extensively occur in the NCC (Figure 1). They record regional rifting events and provide useful information for paleocontinental reconstruction and for the rotation of cratonic blocks (Hou, *et al.*, 2006a). The NCC is composed of three Archean tectonic units: the Eastern Block (EB), the Western Block (WB), and the Central Orogenic Belt (COB) (Kusky and Li., 2003). Dyke swarms in the northern Shanxi and Luliang areas, WB have been researched variously, while those in the western Shandong, EB have not been researched enough.

Geological setting

The studied dykes are located in a quadrilateral area among Jinan, Zibo, Linyi and Jining in Western Shandong (Figure 1), EB of the NCC. The strikes of the dykes in the southern part are NS-trending or even NNE-trending, while those in the northern part are NNW-trending, and are vertical to the COB if eliminating the influence of the extension of Bohai Basin (Hou *et al.*, 2001). The change of the strikes of the dykes from the southern part to the northern part is gradual.

Field investigation shows that the dyke swarms intrude Archean geniss and granulite, Palaeoproterozoic quartzite and Mesoproterozoic rocks of Changcheng System. They are covered by Neoproterozoic magnetite quartzite, and weathering crusts and fine branches of the dykes are found at the bottom of the caprocks.

Figure 2. Field photographs of the dykes



(a) Cover of the dyke and the weathering crust on the bottom of the cover.

(b) Vertical inclination of the dyke. (c) Chilled margin of the dyke and baked margin of the host rocks. (d) Tensional breccias in the contact zone between the dyke and the host rock.

Many precise ages of the Precambrian mafic dyke swarms in the EB have been published in recent papers. Zhuang *et al.* (1995) gave a K-Ar age of 1767 Ma for the diabase dykes at Mt. Taishan. A diabase dyke at Xiafeng in western Shandong has yielded a Sm-Nd age of 1718 Ma (Wang, 1991). Similarly, Hou *et al.* (2006a) gave a SHRIMP zircon U-Pb age of 1830±17 Ma for a large mafic dyke at Mt. Taishan in the EB. From the extensive previous geochronology it can be established that the ages of these mafic dyke swarms span between 1.83 Ga and 1.71 Ga.

These ages suggest that the mafic dyke swarms of the EB were emplaced at the same time as the cf. 1.8 Ga extensional event that followed cratonization of the NCC.

Representative thin and polished sections show that the primary mineralogy in most dykes generally consists of plagioclase, augite and subordinately biotite, and the rocks have typical diabasic texture.

These dykes are undeformed and unmetamorphosed with chilled margins that exhibit sharp contacts with the host rocks. The thicknesses of individual dykes are variable although values of 10 m are most frequent.

Extension ratio of the EB

The characteristics of the boundaries of the mafic dykes suggest that the pre-existing fracture system into which the mafic dyke swarms intruded was formed in an extension regional stress field. First, chilled margins on both sides of the dyke and baked margins of the host rocks on the contacting boundary with the dykes exist widely. Second, the abundant xenoliths and xenocrysts derived from the host rocks have been found on the edges of the dykes. Third, some tensional breccias are found in the contact zone between the dykes and the host rocks, which are composed of basic matrix and granitic breccias and have apparent edges and corners. At last, most of the dykes have irregular boundaries.

Dyke swarms are regarded as valid markers for extension event. Crustal extension in the EB was calculated based on the width statistics of dyke swarms on 7 survey lines. The formula

$$\lambda = \frac{\Sigma d_i}{(L - \Sigma d_i)}$$

was employed in the calculation, where λ is the extension ratio; Σd_i is the total width of dykes on the survey line and L is the length of survey line cross the observed dyke swarms (Hou *et al.*, 2006b). Local extension ratios were calculated and are presented in (Table 1). An average crustal extension ratio of 0.43% was obtained by the calculation of the extension ratio for the EB, which was contributed by the mafic dyke swarms. The small magnitude of overall extension suggests that the mafic dyke swarms were emplaced as limited elastic fractures in the EB, and indicates the EB had become a brittle plate prior to the emplacement of the mafic dyke swarms.

Table 1. The calculation results of extension ratio on the Late Paleoproterozoic mafic dyke swarms of the EB

Profile names	Length of profile (L)(m)	Total width of dykes (Σd_i)(m)	Extension ratio (λ)(%)	Region
A-A'	57100	125	0.22%	Taishan
B-B'	9900	60	0.61%	Laiwu
C-C'	6600	60	0.92%	Laiwu
D-D'	7700	70	0.92%	Mengyin
E-E'	7800	60	0.78%	Mengyin
F-F'	7700	60	0.79%	Linyi
G-G'	15400	50	0.33%	Linyi
		Average extension	0.43%	EB

Mechanism of dyke emplacement

The chilled margins of these dykes have reserved abundant flow structures, such as scours, mineral lineations, orientational xenoliths and so on. The orientations of these marks were controlled by the laminar flow of the magma, and could reflect the characteristics of the magma activity including the direction and way of the dyke emplacement (Hou *et al.*, 2003).

Morphology of individual dyke

Most of the dykes in the EB are vertical and pinch out downward, and the bottom of the dyke is not batholith or stock, as a result the magma may not intrude vertically from below. Most of the dykes extend from NNW to SSE for hundreds of meters or even tens of kilometers, and their widths may diminish gradually and pinch out at last. There are some dyke branches in the southern segments of the dykes and intruded into the country rock along the dominant orientation. These features of the dykes indicate that the magma flowed from NNW to SSE.

Scour marks

As the high temperature magma intrudes into the channel, the contact part with the cold host rock cools faster than other part, resulting in increasing the viscosity and decreasing the velocity of this part. As a result, the middle part with higher velocity is hindered by the contact part causing scour marks on the inner wall of the dyke. These scour marks are wedge or tabular shaped grooves, and mostly not smooth. Besides, if the contact part cools fast enough, scratches may be caused on the inner wall of the dyke. The orientation of the scratches and the heads of the scour marks indicates the flow direction of the magma.

The dykes in the EB have plenty of scour marks and scratches, which indicate that the magma intruded subhorizontally.

Mineral lineation

Due to the difference of the velocity between the middle and the margin of the magma, simple shear may happen resulting in the rotation and orientation of some columnar or tabular minerals, such as plagioclase. The acute angle between the long axis of the minerals and the chilled margin of the dyke points an opposite direction with the magma flow. In addition, the long axes of the phenocrysts plunge to the magma source at about 20°.

The dykes in the EB developed abundant orientated phenocrysts, and these flow microstructures have no trace of tectonism. The observation of thin sections suggests that the magma flow direction indicated by these flow structures is from the North to the South.

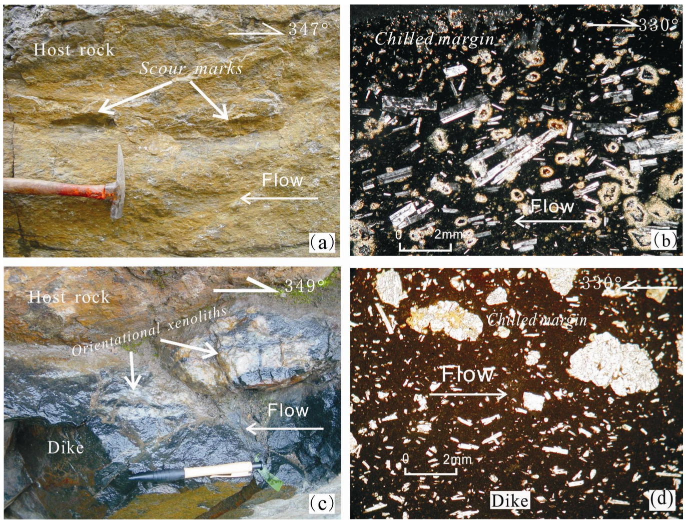
Orientational xenoliths

As has been discussed above, the dyke swarms in the EB intrude pre-existing tensional fractures. In this process, the broken fragments of the host rocks may be captured by the magma, and become xenoliths. Similarly as the rotation and orientation of the mineral lineations, the long axes of the xenoliths indicate the flow direction of the magma.

The dykes in the EB also developed some orientated xenoliths. The field evidence suggests that the magma flow direction indicated by these flow structures is from the North to the South.

The flow of magma inside fractures is helpful for us to understand how continental dyke swarms emplace. The research on the dyke swarms of the EB indicates that the paleostress field offered the space for the magma, and the flow structures of the dykes indicate the magma intruded subhorizontally from the North to the South.

Figure 3. Flow structures of the dyke



(a) Scour marks. (b) Mineral lineation. (c) Orientational xenoliths. (d) Orientational xenoliths under microscope.

Conclusions

Field evidence and thin section observations indicate that the dyke swarms of the EB are similar with those of the WB in distribution characteristics, morphology, petrochemistry, and so on. They were formed in the same mechanism and unified paleostress field, and could be researched as a unit.

The study of the magma flow in the fractures is useful to understand how the dyke swarms form. The researches on the dyke swarms of the EB indicate that the paleostress field offered the space for the magma, and the flow structures of the dykes indicate the magma intruded subhorizontally into the pre-existing fractures.

Some writers have given the result of the simulation of the paleostress field of the NCC (Hou *et al.*, 2006b). The result suggests that extensional fractures were widely formed under the compression from the northern and southern boundaries of the NCC, and offered space for the magma to form the dykes.

Based on the flow structures of the dykes and the previous research on the geochemistry and the magma source, the dyke swarms of the EB are related to the COB similarly as the mafic dyke swarms of the WB.

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