Zircon U-Pb age, geochemical, and Sr-Nd isotopic constraints on the origin of Late Carboniferous mafic dykes of the North China Craton, Shanxi Province, China

Abstract As the special result of lithospheric extension, nowadays, the investigation on geology and geochemistry of the mafic dykes (e.g., lamprophyre, dolerite, diabase porphyrite, etc.) has been given special attention. The mafic dykes mainly distribute in America, Canada, Brazil, Australian and China. In addition, the ages of these dykes are between 2.4 Ga and 1.0 Ga. At present, the Mesozoic and Cenozoic mafic in China were found in North China Craton (NCC), southern China, Tibet and Tarim basin. The studied mafic dykes came from Shanxi Province, northern NCC. Herein, we report U-Pb zircon ages, whole-rock geochemistry, and Sr-Nd isotopic data for representative samples of these dykes. Laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Pb analysis of zircons yielded a consistent Late Carboniferous (293.4 ± 1.7 Ma) age for one sample of the rocks analyzed during this study. Dolerites within the study area have a narrow range of compositions (SiO$_2$ = 50.78% ~ 51.35%, TiO$_2$ = 2.16% ~ 2.32%, Al$_2$O$_3$ = 14.53% ~ 15.08%, Fe$_2$O$_3$ = 12.42% ~ 12.66%, MnO = 0.13% ~ 0.16%, MgO = 5.14% ~ 5.35%, CaO = 7.93% ~ 8.25%, Na$_2$O = 3.52% ~ 3.78%, K$_2$O = 1.01% ~ 1.14%, and P$_2$O$_5$ = 0.24% ~ 0.36%). The dolerites are enriched in light rare earth elements (LREE), large ion lithophile elements (LILE; i.e., Ba, K, and Sr) and high field strength elements (Nb, Ta, and Zr), and depleted in Th, Pb, Nb, P, and Ti. These mafic dykes have relatively uniform ($^{87}$Sr/$^{86}$Sr) values (0.70422 ~ 0.70423), positive εNd(t) values (5.8 ~ 6.1), and invariant neodymium model ages (${t_{DM1}}$ = 0.67 ~ 0.72 Ga, $t_{DM2}$ = 0.57 ~ 0.59 Ga). These data suggest that these dykes formed from magmas derived from partial melting of a depleted asthenospheric mantle source that fractionated olivine, pyroxene, and Ti-bearing phases without assimilating significant amounts of crustal material. In summary, the generation and emplacement of mafic magmas in Shanxi Province, northern NCC can be attributed to post-subduction and collision (e.g., Paleo-Asian Ocean, Mongolia China Block) lithosphere extension.

Key words Late Carboniferous; Mafic dykes; Origin; Northern NCC; Siberian Block

摘 要 作为岩石圈伸展拉张背景侵位的特征岩石,基性岩墙群(煌斑岩、辉绿岩和辉绿玢岩等)地质和地球化学研究日益受到地质研究者的关注。研究显示,基性岩墙在全球范围主要分布在美国、加拿大、巴西、澳大利亚和中国等地区,且年代框架主要集中于前寒武纪时期(2.4 Ga, 2.1 Ga, 1.8 Ga, 1.4 Ga, 1.0 Ga)。目前,国内中生代以来基性岩墙群主要出露于华北克拉

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1 Introduction

NE-SW and NW-SE striking mafic dykes are widespread in the North China Craton (NCC; Liu et al., 2008a, b, 2009, 2012a, b, 2013), and are the product of lithospheric extension (Hall, 1982; Hall and Fahrig, 1987; Tarney and Weaver, 1987; Zhao and McCallough, 1993). These rocks provide valuable information on the processes involved in extension, the nature of the mantle beneath this region, and the temporal and spatial evolution of this area, as well as enabling reconstructions of the agglomeration, extension, and rifting apart of continental blocks. Despite this, little research has been undertaken on mafic dykes within the NCC, and the majority of previous research has focused solely on Precambrian and Mesozoic mantle-crust interaction (e.g., Chen and Shi, 1983; Shao and Zhang, 2002; Zhang and Sun, 2002; Shao et al., 2003; Zhai et al., 2003, 2004; Xu, 2004; Yang et al., 2004; Liu et al., 2005, 2006, 2008a, b, 2009, 2012b, 2013; Peng, 2010; Peng et al., 2005, 2007, 2008, 2010, 2011b, Hou et al., 2006; Wang et al., 2007; Hu et al., 2008; Lin et al., 2008; Wu et al., 2008; Zhu et al., 2008; John et al., 2010; Li et al., 2010). In contrast, little research has been undertaken on Late Paleozoic (especially Devonian-Permian) mafic dykes of Shanxi Province, located in the northern NCC.

This lack of research means that further studies on the geochronological, geochemical, and isotopic characteristics of Late Paleozoic mafic dykes of the northern NCC are required. Here, we present new laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) zircon U-Pb geochronological, petrological, major, trace and rare-earth element geochemical, and Sr-Nd isotopic data for representative mafic dykes within the northern NCC. The aim of this work was to constrain the timing of emplacement and the petrogenesis of the magmas that formed these mafic dykes.

2 Geological setting and petrography

The NCC consists of an N-S striking mid-continental Proterozoic orogenic belt and Archean eastern and western blocks (Zhao et al., 2001; Fig. 1a). The study areas in the present paper are located in the Xituanbao and Tatong areas of northern Shanxi Province (samples XTB1 to XTB16), within the northern NCC. Mafic dolerite dykes from this area were sampled during this study (Table 1; Fig. 1b). These dykes were intruded into gneisses and granite country rocks of unknown age; the other major country rock in this area is dolomite (Fig. 1b). Individual mafic dykes are vertical, and strike NE-SW. These dykes are commonly 0.05 ~ 2.4 km wide and 2.2 ~ 18.0 km long (Fig. 1b), and representative photomicrographs of mafic dykes in the Xituanbao area (samples XTB-2 and XTB-8) are provided in Fig. 2. All of the mafic dykes are dolerites. They have typical doleritic/diabasic textures and consist of medium-grained clinopyroxene (2.5 ~ 4.5 mm) and lath-shaped plagioclase (1.5 ~ 3.0 mm) phenocrysts (32 ~ 35% of the rock mass) in a groundmass (65 ~ 68% of clinopyroxene (0.03 ~ 0.05 mm), plagioclase (0.04 ~ 0.05 mm), minor magnetite (~0.05 mm), and chlorite.

3 Analytical procedures

3.1 LA-ICP-MS U-Pb dating

Zircons were separated from one sample (XTB01) using conventional heavy liquid and magnetic techniques at Langfang Regional Geological Survey, Hebei Province, China. The internal and external structures of zircons were observed using transmitted and reflected light and cathodoluminescence (CL) petrography at State Key Laboratory of Continental Dynamics, Northwest University. Zircon U-Pb dating was performed by LA-ICP-MS (Table 1; Fig. 3) using an Agilent 7500a ICP-MS instrument, equipped with a 193nm excimer laser at State Key Laboratory of Geological Processes and Mineral Resources, China University of Geoscience, Wuhan, China. A 24 m laser spot diameter was used during analysis, a #1500 zircon standard was used for calibration, and a NIST 610 standard was used for optimization. Grain mount surfaces were washed in dilute HNO3, and pure alcohol prior to analysis to remove any potential lead contamination. The analytical methodology followed Yuan et al. (2004) and Liu et al. (2010), and common Pb was corrected following Andersen (2002). The resulting data were processed using the GLITTER and IsoPLOT programs (Ludwig, 2003; Table 1; Fig. 3), and uncertainties on individual LA-ICP-MS analyses are quoted at the 95% (1σ) confidence level.
Fig. 1 Location of the sampling transect undertaken during this study (a) and map showing the geology, the distribution of the mafic dykes, and sampling locations within the study area (b).

3.2 Whole-rock geochemistry

The whole-rock and Sr-Nd isotope geochemistry of 16 mafic dyke samples was determined. Prior to analysis, samples were trimmed to remove altered surfaces, cleaned with de-ionized water, and crushed and powdered in an agate mill. Major element concentrations were determined using a PANalytical Axios-advance X-ray fluorescence spectrometer (XRF) at State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China. Major element concentrations were determined on fused glass discs and these analyses have an analytical precision of <5%, as determined using the GSR-1 and GSR-3 Chinese National standards (Table 2). Losses on ignition values (LOI) were determined on 1g of powder that was heated to 1100°C for 1 hour. Trace element concentrations were determined by ICP-optical emission spectrometry (OES) and ICP-MS at National Research Center of Geo-analysis, Chinese Academy of Geological
3.3 Sr-Nd isotopic analyses

Triplicate analyses yielded a reproducibility of <5% for all elements, and analyses of OU-6 and GBPG-1 international standards were in agreement with recommended values (Table 3).

Table 3 Major element concentrations (wt %) for the mafic dykes from Shaxi Province, northern NCC, China

<table>
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<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
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<th>Total</th>
<th>Mg°</th>
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<td>5.23</td>
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<td>1.12</td>
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<td>0.61</td>
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<td>8.15</td>
<td>3.78</td>
<td>1.09</td>
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<td>0.54</td>
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<td>5.23</td>
<td>8.12</td>
<td>3.63</td>
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<td>0.52</td>
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Note: LOI = loss on ignition; Mg° = 100 (Mg/(Mg + Fe)) atomic ratio; RV = recommended values; MV = measured values.

3.3 Sr-Nd isotopic analyses

Rh-Sr and Sm-Nd isotope analysis used sample powders spiked with mixed isotope tracers before dissolution in Teflon capsules with HF + HNO₃ acids, and separation using conventional cation-exchange techniques. Isotopic measurements were undertaken using a Finnigan Triton Ti thermal ionization mass spectrometer at State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. Procedural blanks were <200pg for Sm and Nd, and <500pg for Rh and Sr. Mass fractionation corrections for Sr and Nd isotopic ratios used 88Sr/86Sr and 146Nd/144Nd values of 0.1194 and 0.7219, respectively, and analysis of the NBS987 and La Jolla standards yielded values of 87Sr/86Sr = 0.710246 ± 16 (2σ) and 143Nd/144Nd = 0.511863 ± 8 (2σ), respectively; the results of these analyses are given in Table 4.
Table 3 Trace element compositions ($\times 10^{-6}$) of the mafic dyke from Shanxi Province, northern NCC

<table>
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<th>Sample</th>
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<sup>(La/Yb)_N</sup> = 9.4, 9.1, 8.8, 9.2, 9.3, 9.3, 8.8, 8.9, 9.4, 8.8, 9

δEu<sub>N</sub> = 1.11, 1.13, 1.14, 1.1, 1.12, 1.12, 1.14, 1.13, 1.12, 1.13, 1.13

Note: values for GBPG-1 are from Thompson et al. (2000), and values for OU-6 are from Potts and Kane (2005)
4 Results

4.1 Zircon U-Pb dating

Euhedral zircons separated from sample XTB01 are clean and pristine, and contain magmatic oscillatory zoning (Fig. 3). The (10% of 15 zircons from this sample) yielded a weighted mean U-Pb age of 203 ± 1 Ma 4 (2σ; 95% confidence interval; Table 1: Fig. 3). This age is the best estimate of the crystallization age of the mafic dykes in the Xintang area; no inherited zircon cores were identified during this study.

4.2 Whole-rock geochemistry

The whole-rock geochemical compositions of mafic dykes analyzed during this study are given in Table 2 and Table 3. The mafic dykes have a narrow range of chemical compositions, with CaO = 7.93%~8.25% and MgO = 5.14%~5.35%, which fall within the calc-alkaline field in a Na-O vs. K diagram (Fig. 4a). The dykes also plot within the alkali-silica (TAS) diagram (Fig. 4b), and the dykes also plot within the alkali-silica (TAS) diagram (Fig. 4a).

Fig. 4 Classification of the mafic dykes within the NCC.

Table 4 Sr-Nd isotope compositions of the mafic dykes from Shanxi Province, northern NCC, China

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sm (×10^-6)</th>
<th>Nd (×10^-6)</th>
<th>Rb (×10^-6)</th>
<th>Sr (×10^-6)</th>
<th>87Rb/86Sr</th>
<th>87Sr/86Sr</th>
<th>2σ</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>2σ</th>
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<th>εNd(t)</th>
<th>tDM1(Ga)</th>
<th>tDM2(Ga)</th>
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<tr>
<td>XTB-1</td>
<td>6.16</td>
<td>25.6</td>
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<td>0.704838</td>
<td>8</td>
<td>0.704226</td>
<td>0.1455</td>
<td>10</td>
<td>0.512846</td>
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Note: Calculations used the Chondrite Uniform Reservoir, λRb = 1.42 × 10^-11 year^-1 (Steiger and Jäger, 1977), and λSm = 6.54 × 10^-12 year^-1 (Lugmair and Hart, 1978)
by LREE enrichments and HREE depletions, with a wide range in \((\text{La/Yb})_\text{N} (8.2 ~ 9.9)\) and \(\delta\text{Eu} (1.10 ~ 1.13)\) values (Table 3; Fig. 6a). Dykes within the study area are LILE (i.e., Ba, K and Sr) and Nb, Ta, and Zr enriched, and Th, Pb, Nd, P, and Ti depleted in primitive mantle-normalized trace element diagrams (Fig. 6b).

4.3 Sr-Nd isotopes

The Sr-Nd isotopic compositions of eight representative mafic dykes were analyzed (Table 4), yielding uniform \((^{87}\text{Sr}/^{86}\text{Sr})\), values (0.70422 ~ 0.70423) and \(\varepsilon_{\text{Nd}}(t)\) values (5.8 ~ 6.1), suggesting that they formed from magmas derived from a depleted mantle source (Fig. 7).

5 Genesis of the mafic dyke magmas

5.1 Mantle source

Mafic dykes in the study area contain low SiO2 concentrations (50.78% ~ 51.35%) (Table 2), suggesting derivation from an ultramafic (i.e., mantle) source, and not from melting of crustal material. This hypothesis is supported by the relatively high concentrations of MgO (5.14% ~ 5.35%), Ni \((117 \times 10^{-6} ~ 141 \times 10^{-6})\), and Cr \((105 \times 10^{-6} ~ 135 \times 10^{-6})\), and the elevated Mg# values (44 ~ 48) of the mafic dykes. Crustal rocks can be excluded as a potential source of the magmas that formed these dykes, as partial melting of any crustal rocks (e.g., Hirajima et al., 1990; Zhang et al., 1995a; Kato et al., 1997) or lower crustal intermediate granulites within the deep crust (Gao et al., 1998a, b) would produce high-Si, low-Mg melts (i.e., of granitoid composition). In addition, the mafic dykes have low initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios (0.70422 ~ 0.70423) and uniformly positive uniform \(\varepsilon_{\text{Nd}}(t)\) values (5.8 ~ 6.1; Table 4), consistent with derivation from a depleted lithospheric mantle source or from the asthenospheric mantle. It is generally accepted that the lithospheric mantle has enriched initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios, and generally has low \(\varepsilon_{\text{Nd}}(t)\) values (Zhang et al., 2005), whereas asthenospheric mantle magma is likely to be isotopically depleted, with low \((^{87}\text{Sr}/^{86}\text{Sr})\), and high \(\varepsilon_{\text{Nd}}(t)\) values (Saunders et al., 1992). These data suggest that the magmas that formed the mafic dykes of the NCC studied here were sourced from the asthenospheric mantle.
5.2 Crustal contamination

Crustal contamination can cause significant enrichment in the Sr-Nd isotopic composition of basaltic rocks. The mafic dykes analyzed during this study have depleted Sr isotopic compositions (0.70422 ~ 0.70423) and positive $\varepsilon_{Nd}(t)$ values (5.8 ~ 6.1), suggesting that the magmas that formed these dykes assimilated little or no crustal material prior to emplacement. Furthermore, crustal assimilation would cause significant variation in the Sr-Nd isotope composition of a magma, and would also result in a positive correlation between MgO and $\varepsilon_{Nd}(t)$ values (5.8 ~ 6.1), and a negative correlation between MgO and ($^{87}$Sr/$^{86}$Sr) ratios (0.70422 ~ 0.70423), yet these features are not observed in the dolerite samples analyzed here (figure not shown).

Finally, the lack of inherited zircons in these dykes indicates that the magmas that formed these dykes underwent negligible crustal contamination. In summary, the geochemical and isotopic compositions of the dolerites analyzed during this study support their formation from magmas derived from a depleted asthenospheric mantle source that underwent little to no crustal contamination.

5.3 Fractional crystallization

Mafic dykes within the Xituanbao area have high Mg$^+$ values (44 ~ 48; Table 2), inconsistent with formation from magmas that underwent significant crystal fractionation. This lack of fractionation is further supported by the lack of correlation between MgO and other major elements ($\text{SiO}_2$, $\text{TiO}_2$, $\text{Fe}_2\text{O}_3$, $\text{Na}_2\text{O} + \text{K}_2\text{O}$, $\text{MnO}$, and $\text{P}_2\text{O}_5$) (Fig. 5). Nevertheless, it is generally thought that mafic magmas undergo fractionation of olivine, pyroxene, and Ti-bearing phases (rutile, ilmenite, titanite, etc.; Liu et al., 2005, 2006, 2008a, b, 2009, 2012b, 2013), as illustrated by the fact that the mafic dykes analyzed during this study plot along a visible fractionation trend on a La vs. La/Sm diagram (Fig. 8). This is further supported by the low MgO (Mg$^+$) and Ni contents (Table 2 and Table 3), as well as the Ti depletion (Fig. 6b). However, the magmas that formed these dykes underwent some separation of plagioclase, and the presence of small number of feldspar cumulates, as evidenced by the presence of weak positive Eu anomalies in chondrite-normalized REE patterns (Fig. 6a).

5.4 Genetic model and NCC destruction

Mafic dykes in China are thought to have formed from magmas derived from partial melting of either the lithospheric or asthenospheric mantle (Liu et al., 2005, 2006, 2008a, b, 2009, 2012b, 2013). The data presented here suggest that the magmas that formed the mafic dykes within the study area were
derived from partial melting of a depleted region of the asthenospheric mantle. In addition, the fact that the mafic dykes are LREE-enriched and HREE-depleted suggests that these magmas were generated during partial melting of a region of the mantle that contained residual garnet.

However, a dynamic model is required to help further decipher the origin of these rocks; most importantly, we need to determine whether subduction of either the ancient Pacific Plate or the Yangtze lithosphere contributed in any way to the formation of these dykes, especially as these dykes provide key constraints on the petrogenesis of magmatism within both the NCC and eastern China. The timing and direction of collisional tectonics within the NCC (Engebretson et al., 1985; Xu et al., 1993; Zhang et al., 1995b; Xu and Chen, 1997; Meng and Zhang, 1999; Hu et al., 2004; Liu et al., 2005; Zhang et al., 2005) means that we can exclude the possibility of any contributions from these two plates.

The tectonic evolution of the northern NCC, including the location and timing of collision between the northern NCC and the Siberian Block, is a controversial and important issue (Tang, 1990; Shao, 1991; Hong et al., 1995; Zhang et al., 2007; Zhang et al., 2008; Luo et al., 2009). However, it is generally agreed that collision took place before the Early Permian (i.e., Silurian or Devonian; Zhang et al., 2008). The study area underwent relaxation and extension after this collision, resulting in crustal thinning and decompression partial melting of the asthenospheric mantle, processes that ultimately resulted in the emplacement of mafic dykes within the study area. Nevertheless, the two plates were separated from each other; they could not collide in Carboniferous evidenced by plate reconstruction. As such, an alternative model that accounts for the formation of these mafic dykes is needed, and is presented below.

Prior to carboniferous, the subduction of Paleos-Asian Ocean and the collision of Mongolia China Block occurred (Shao, 1991; Chen et al., 2000, 2001; Yan et al., 2000). Consequently, NCC lithosphere extension appeared. We therefore propose the following genetic model to account for the presence of mafic dykes within the northern NCC: (a) prior to subduction and collision, the NCC, Paleos-Asian Ocean and Mongolia China plates were three independent blocks; (b) subduction or collision between these blocks occurred before the Carboniferous, resulting in many slab windows and slab breakoff; and (c) lithosphere extension and some tectonic weak zone (e.g., slab window and breakoff) occurred. In this case, the extension led to partial melting of asthenospheric mantles beneath the NCC. These partial melts were the parental mafic magmas of the mafic dykes within the study area. These magmas underwent fractionation, but no crustal contamination, during ascent and emplacement of the mafic dykes within the study area.

For NCC destruction, the carbonatites were derived from partial melting of asthenospheric mantle based on the above interpretation and discussion, implying the NCC destruction might occur in Carboniferous, which is important for the evolution of the NCC.

6 Conclusions

The geochronological, geochemical, and Sr-Nd isotopic data presented here have allowed the following conclusions to be drawn:

1. Zircon LA-ICP-MS U-Pb dating of the mafic dykes in Shanxi Province, China, indicates a Late Carboniferous (293.4 ± 1.7 Ma) age of crystallization.

2. These mafic dykes were derived from partial melting of a depleted asthenospheric mantle source, and the parental magmas of these dykes underwent fractionation of olivine, pyroxene, and Ti-bearing phases (rutilite, ilmenite, and titanite) during ascent and emplacement. Emplacement of the dykes was associated with negligible crustal contamination.

3. The generation and emplacement of the mafic magmas in Shanxi province, the northern NCC can be attributed to post-subduction and collision (e.g., Paleo-Asian Ocean, Mongolia China Block) lithosphere extension.

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References


Uranium metagenesis in South China and its relationship to crustal extension during the Cretaceous to Tertiary. Economic Geology, 103 (3): 583 – 598


Li TS, Zhai MG, Peng P, Chen L and Guo JH. 2010. Ca. 2.5 billion year old coeval ultramafic-mafic and syenitic dykes in Eastern Hebei; Implications for crustalization of the North China Craton. Precambrian Research, 180 (3-4): 143 – 155


郝济安. 1991. 中朝板块北缘中地壳演化. 北京: 北京大学出版社, 136


王涛, 郑亚东, 张进成, 王新社, 曾令森, 童英. 2007. 华北克拉通中生代伸展构造研究的几个问题及其在岩石圈减薄研究中的意义. 地质通报, 26 (9): 1154 – 1166


徐义刚. 2004. 华北岩石圈减薄的时空不均一特征. 高校地质学报, 10 (3): 324 – 331


附中文参考文献

