

Spatial and Temporal Distribution Patterns of Mafic Dyke Swarms in Central Asia: Results from Remote-Sensing Interpretation and Regional Geology



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Abstract Mafic dykes in continents are a special type of intrusive rock formed by different tectonic events including earlier fracturing deformation in host rocks and successive magma intrusions originating at depth. Dyke swarms indicate regional crustal deformation related to continental formation and evolution, and play the role of messenger regarding magma activities from the deeper crust or even mantle. The large number of mafic dykes in Central Asia hold the keys to resolve some debated tectonic problems such as subduction-accretion-collision processes during the formation of Central Asia (the western part of the Central Asian Orogenic Belt). However, spatial-temporal distribution patterns of mafic dykes in this vast area have not been comprehensively described and discussed to date. This study carried out a fundamental work on the spatial-temporal distribution patterns of dykes in Central Asia, and is intended to provide basic preparation for more in-depth studies in the future. In Enhanced Thematic Mapper Plus (bands 7, 4, and 2) images, major mafic dykes (greater than 5 m wide) displayed as dark-colored linear objects against their host rocks, and can be distinguished and plotted one-by-one and further analyzed using Geographic Information System software. The results indicate that more than 99% of the mafic dykes were emplaced in the Eastern Tianshan and Beishan, Western Mongolian-Altai, Eastern Junggar, North and West bank of Balkhash, Western

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R. K. Srivastava et al. (eds.), *Dyke Swarms of the World: A Modern Perspective*,

Springer Geology, https://doi.org/10.1007/978-981-13-1666-1_8

Junggar, and Chingis-Taerbahatai. Most dykes formed during the Late Paleozoic, and the occurrence of these dykes is a result of various regional fracturing processes along different tectonic boundaries as well as immense magmatic intrusions (related to subduction, post-collisional processes, or large igneous provinces/giant mantle plumes). Other much older dykes were emplaced in the marginal areas of cratons, such as the Neoproterozoic dykes that intruded into the metamorphosed basement of the Tarim Craton (Aksu blueschist complex) and dykes emplaced in the Kuruktag area, which record the break-off history of the cratons. This study provides a general framework of mafic dykes in Central Asia on a large scale, and more intensive studies of mafic dykes at medium to small scales in different areas need a combined application of different observation methods, which will provide a better understanding of the continental evolution of Central Asia.

Keywords Dyke swarms · Central Asia · Satellite images · Visual interpretation
Tectonic evolution

1 Introduction

As a special type of intrusive rock, mafic dykes are the consequence of earlier fracturing within the upper crust overprinted by successive magma intrusion from the deeper crust or even mantle. Compared to dykes within oceanic crust (mafic sheeted dyke complex in ophiolite suite; Moores 1982), continental mafic dykes are much more complicated; nevertheless, they are significant for re-constructing tectonic histories and geodynamical settings at different scales. At a continental scale, dyke swarms are considered to represent the break-off and destruction of cratons (e.g. Morgan 1971; Campbell and Griffiths 1990; Goldberg and Butler 1990; Zhao and McCulloch 1993; Kamo and Gower 1994; Zhao and McCulloch 1994; Kamo et al. 1995; Li et al. 2012), such as the largest dyke on Earth (the Giant Dyke) in Zimbabwe (Wilson 1982, 1996; Mukasa et al. 1998), dyke swarms in the North China craton (Li et al. 1997; Hou et al. 1998; Li et al. 2001; Shao and Zhang 2002; Hou et al. 2003; Peng et al. 2004; Peng 2010; Liu et al. 2017; Wang et al. 2017; Zhang and Cheng 2017), and huge radial dyke swarms that are indicative of mantle plumes (e.g. LeCheminant and Heaman 1991; Mertanen et al. 1996; Ma et al. 2000; Lu and Jiang 2003; Xu et al. 2007). On a regional scale, dykes of different strike and width elaborate spatial distribution patterns of dyke-filled fractures and intensities of mafic magmatic intrusions. The dykes play an important role in the formation of new crust in some orogenic zones (e.g. Li et al. 2005a; Chen et al. 2013). Moreover, some mineral resources are closely linked to dyke swarms (e.g. Oberthur et al. 1997; Schoenberg et al. 2003; Luo et al. 2008, 2012; Liu et al. 2014).

The significance of dyke swarms is increasingly highlighted by geological societies. It can be concluded from the seven International Dyke Conferences (IDCs) held in recent decades and numerous published papers that studies of dyke swarms can be divided into the following aspects: (1) Geochemical information

of dyke rocks, which is very important to understand the processes of continental break-up, giant mantle plumes, and the interactions between mantle and crust; (2) Transportation processes and mechanisms during intrusion of dyke magma within the fractures in crust, as well as their contributions to continental growth and mineral enrichment; (3) Later deformation acting on previous dykes, for instance, some dykes are cut-off or curved; and (4) Formation mechanisms of dyke-filled fractures in host rocks, and the driving paleo-stress conditions. Central Asia is a major part of the Asian-European continent, and occupies most of the western Central Asian Orogenic Belt (CAOB; Jahn et al. 2000; Jahn 2004; Windley et al. 2007; Xiao et al. 2008). The crust of this vast area was mainly created by subduction and closure of the paleo-Asian Ocean (PAO) and a collage of continental slices, islands, marginal accretionary complexes, and sporadic oceanic crust fragments (Şengör et al. 1993; Windley et al. 2007; Li et al. 2009b; Xiao et al. 2009; Xiao et al. 2010a, b). To date, some crucial issues related to accretion and collision evolution histories in different parts of the CAOB, such as the timing of the closure of the PAO, are still hotly debated (Li et al. 2002b; Shu et al. 2004; Gao et al. 2006; Xiao et al. 2006b; Zhang et al. 2007a). Meanwhile, the existence of Permian large igneous provinces (LIPs) or giant mantle plumes in the Tarim and Eastern Tianshan in Xinjiang (Northwest China) also needs comprehensive discussion (Xia et al. 2004, 2006, 2008; Zhang and Zou 2013). Previous studies have mostly focused on accretionary complexes, granitic rocks, and volcanic and sedimentary rocks. However, the large number of mafic dykes in the CAOB have not paid sufficient attention. Investigations of the spatial-temporal distribution patterns of dykes on a large scale of this area have not been carried out.

Considering this situation, it is crucial to accomplish a survey of the spatial-temporal distribution patterns of dykes in Central Asia to provide fundamental data and instructions for further specific studies, especially discussing the role of mafic dyke swarms in the evolutionary history of the CAOB. Our investigations of the mafic dyke swarms in Central Asia started in 2009, and detailed studies have been carried out in some dyke-concentrated areas (such as the Western Junggar and Eastern Tianshan). This study introduces the methods applied to distinguish and extract dykes from host rocks, and reports the spatial-temporal distribution patterns of dyke-swarms on a large scale in Central Asia.

2 Tectonic Background and Dyke-Related Studies in Central Asia

2.1 Tectonic Background of Central Asia (Western Part of the CAOB)

The CAOB, alternatively known as the Altaids (Şengör et al. 1993) or the North Asian Orogenic Region (NAOR; Li et al. 2006a, 2009b), is situated between the Siberian craton to the north and the Tarim–North China craton to the south (Fig. 1a). It extends

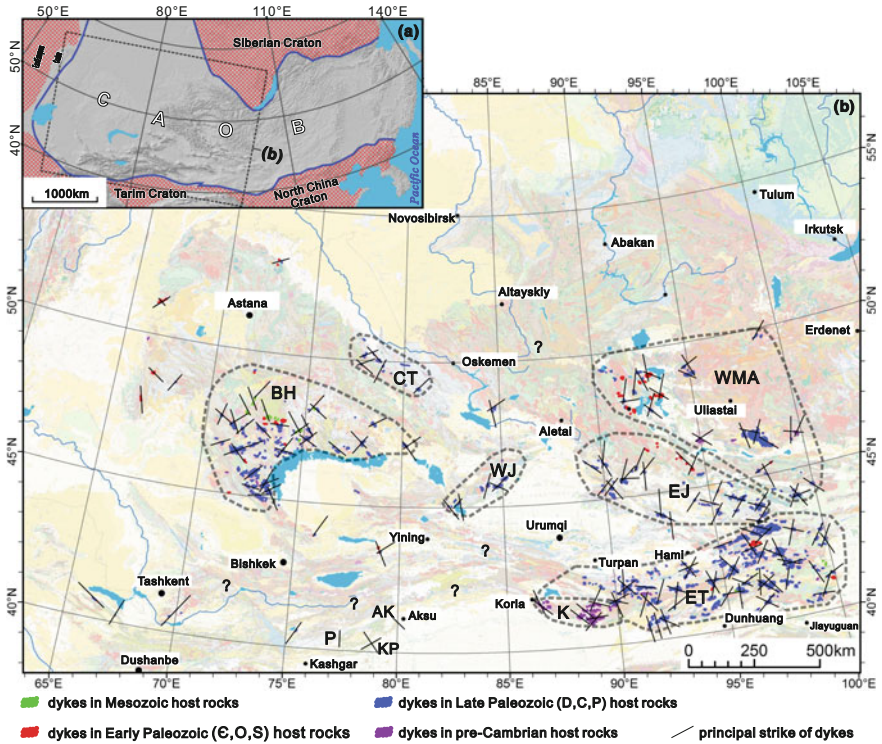


Fig. 1 Location of study area and distribution of mafic dykes in central Asia. **a** Tectonic location of the Central Asian Orogenic Belt. **b** Distribution patterns of dykes in central Asia, resulted from visual interpretation of ETM+ (bands 7, 4, and 2) images. ET: Eastern Tianshan and Beishan; WMA: Western Mongolian-Altai; BH: North and West bank of Balkhash; EJ: Eastern Junggar; WJ: Western Junggar; CT: Chingis-Taerbahatai; K: Kuruktag; AK: Aksu blueschist; KP: Keping; P: Piqiang area. (The dykes are too dense to be displayed as linear features in such a small-scale map. They are displayed as dyke swarms)

from the Ural Mountains in the west to the Pacific Ocean in the east. It is one of the largest Phanerozoic orogens on Earth, and exposes important geological units that can broaden our understanding of the subduction–accretion–collision processes that were active during the assembly of the Asian continent.

In recent years, investigations of key lithological and structural features within the CAOB have provided great insight regarding its general tectonic framework and Phanerozoic evolution, which was dominated by the marginal accretions and collisions between continental blocks during the Late Paleozoic, and the intracontinental orogenic processes that transpired during the Mesozoic and Cenozoic (e.g. Li 1980; Li et al. 2006a; Windley et al. 2007; Xiao et al. 2008; Wilhem et al. 2012). However, some significant issues regarding the evolution of the CAOB are still hotly debated, particularly the timing of closure of the PAO and the geodynamic setting during the Carboniferous–Permian. Xia et al. (2004, 2006, 2008) hypothesized that

the Paleozoic ocean in the region closed in the Late Devonian and that during the Carboniferous and Permian both an intracontinental rift setting and a large igneous province occurred. Li (2004), Li et al. (2006a), Shu et al. (2004), Gao et al. (2006) suggested that the Paleozoic oceans closed in the Late Carboniferous, and the subsequent geodynamic setting was marked by the collision and amalgamation of continental blocks. Meanwhile, Late Carboniferous-Permian magmatism occurred within post-collisional settings (Han et al. 1999; Chen and Jahn 2004; Han et al. 2006). However, other studies argued that the Paleozoic oceans remained until the end of the Permian, and possibly persisted until the beginning of the Triassic (e.g. Li et al. 2002b, 2005b; Zhang et al. 2005; Xiao et al. 2006b; Zhang et al. 2007a).

2.2 *Previous Studies of Dykes in Central Asia*

Mafic dyke swarms in different parts of Central Asia have attracted some attention over the last 10 years (e.g. Zhang et al. 2007b, 2008a; Yin et al. 2009; Luo et al. 2012; Tang et al. 2012; Wang et al. 2015; Yang et al. 2015). For instance, the dykes in Western Junggar have been dated via different methods (Li et al. 2004; Xu et al. 2008; Zhou et al. 2008; Feng et al. 2012a, b; Yin et al. 2012; Zhang and Zou 2013), and the occurrence of diorite dyke swarms have been explained as the result of ridge subduction (Ma et al. 2012) or vertical magmatic intrusion and regional extension during post-collision evolution (Li et al. 2005a). Some curved dykes in Beishan (Sun et al. 2010) and truncated dykes in Eastern Tianshan (Feng et al. 2012c) indicate the shearing sense along local large faults. The correlation of distribution patterns between dykes and mineral deposits is also discussed in some areas (Qi 1993; Luo et al. 2008, 2012).

According to the previous aforementioned studies and observations of this work in different areas, the distribution patterns of mafic dykes are characterized by the following: (1) Most dykes are linear geological bodies with a certain width and length (aspect ratio greater than 10:1). Most dykes in Central Asia are less than 10 m wide, and smaller dykes less than 1 m are also widespread; (2) Dykes are usually intensively exhibited as dyke swarms, in some dyke-concentrated areas, the quantity of dykes is approximately 2–3 orders of magnitude greater than that of major faults; (3) Dykes of different strikes are usually crosscut and displaced among each other, and some displacement along the dykes is too small to be observed in satellite images; and (4) Dykes are usually accompanied by several small faults, some are fault-cut dykes and others are filled by dykes.

3 Data and Methods

3.1 Difficulties of Field Observation on a Large Scale

Field observations are indispensable to investigate individual dyke-segments and dyke swarms in a small area. To describe distribution patterns in a large region such as the whole Central Asia, field observation results of all dyke-emplaced areas (usually with different levels of detail) over the entirety of Central Asia must be collected and summarized. However, in the situation that the dyke-swarms have not been thoroughly investigated at small scales in previous studies, it is impossible to finish this immense task in a quite limited time. As a compromised step, alternatively efficient methods must be tested and applied, to estimate the distribution patterns of dykes on a large scale for the first time.

3.2 Visual Interpretation Method and Employed Data

Through experience of dyke-related surveys in recent years, we have found that a remote-sensing interpretation method is reliable for regional investigations of mafic dykes. Fortunately, most parts of Central Asia are arid and outcrops of dykes are rarely covered by vegetation. In different types of satellite images of different spatial resolutions, mafic dykes are displayed as dark-colored linear objects against lighter-colored host rocks (Fig. 2), and can be easily distinguished using visual interpretation method (Zhang et al. 2007b, 2008a, Feng et al. 2012a, b, c).

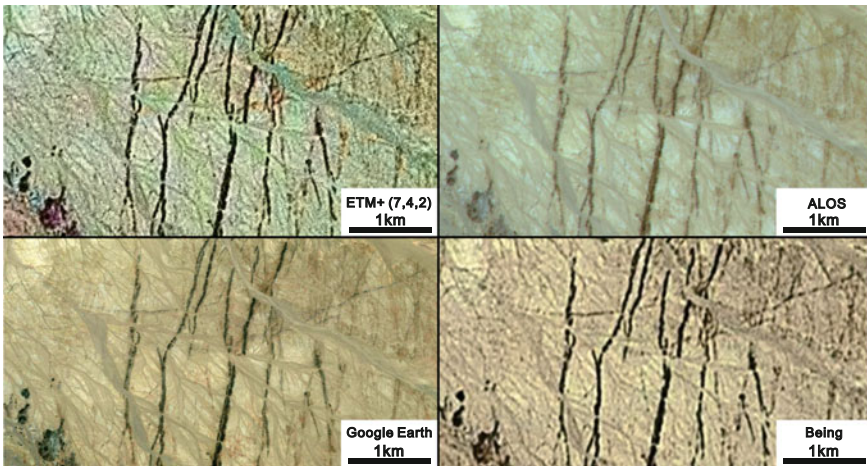


Fig. 2 Mafic dykes displayed as dark-colored linear objects in different satellite images

Numerous ETM+ images were collected covering the whole study area (bands 7, 4, and 2 of the Landsat 7 data are synthesized as red, green, and blue channels, respectively; the product images were freely downloaded from <https://wist.echo.nasa.gov/api/> in 2010). The spatial resolution of the ETM+ images is approximately 14.25 m, which allows one to distinguish major dykes. The images can be imported into ArcGIS software, and each individual dyke segment is visually distinguished and plotted one-by-one and stored as vector-formatted lines in an ArcGIS database. The lengths and strikes of the dykes are calculated by the coordinates of their endpoints automatically. Concentrations of dykes in different areas are analyzed and compared based on an analysis of individual dykes.

3.3 Corroboration and Evaluation of Results

The existence and accuracy of distinguished dykes are corroborated and evaluated in intentionally arranged field surveys. The results show that only major dykes greater than 5 m wide can be correctly distinguished; smaller dykes cannot be seen in ETM+ images.

4 Spatial and Temporal Distributions of Dyke Swarms

4.1 Spatial Distribution Patterns of Dykes on a Large Scale

Visual interpretation using ETM+ images distinguished approximately 30,830 major dykes (more than 5 m wide) emplaced in Central Asia (Fig. 1b).

On a large scale, these dykes are not evenly distributed (Fig. 3), and the optimal directions of the dykes vary among different areas in Central Asia (Fig. 4). More than 99% of the dykes are concentrated in the following areas (from the most to the least): (1) Eastern Tianshan and Beishan (ET); (2) Western Mongolian-Altai (WMA); (3) North and West of Balkhash (BH); (4) Eastern Junggar (EJ); (5) Western Junggar (WJ); and (6) Chingis-Taerbahatai (CT). Eastern Tianshan and Beishan is the most dyke-concentrated area in Central Asia, accommodating more than 60% dykes (Figs. 1b, 3).

Other areas such as the Western Tianshan and Altai in Xinjiang are covered by vegetation or glaciers. The existence and number of mafic dykes in these areas is unknown (see question mark labels in Fig. 1b), and have rarely been reported in previous studies (e.g. the NE–SW trending dykes in the Southwest Altai; Cai et al. 2010).

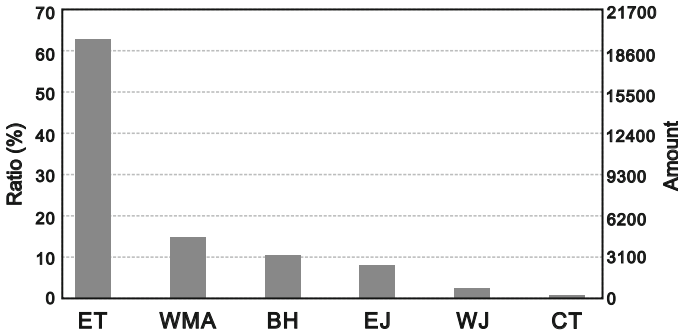


Fig. 3 The amount of dykes in dyke-concentrated areas. ET, WMA, BH, EJ, WJ, and CT stand for the same areas with Fig. 1(b). The ratio refers to the amount of dykes in these areas compare with the whole study area

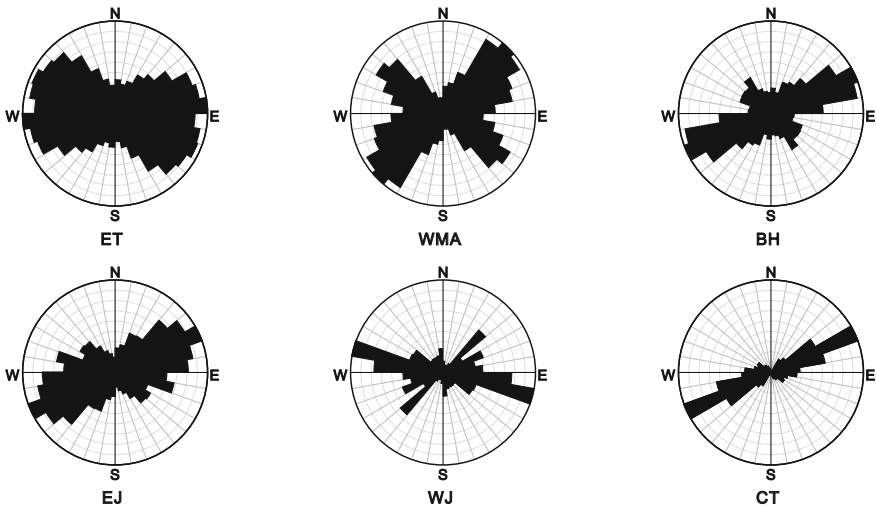


Fig. 4 Rose diagrams of dykes in dyke-concentrated areas. ET, WMA, BH, EJ, WJ, and CT stand for the same areas with Fig. 1(b)

4.2 Temporal Distribution of Dykes

Chronological studies of dykes have not been thoroughly completed in available previous studies thus far. This study discusses the ages of dykes indirectly by: (1) Ages of the host rocks (dykes must be younger than their host rocks); (2) Nearby mafic magmatic events; and (3) regional fracturing events.

According to regional geological maps and published geochronological results, most host rocks of the dykes in Central Asia formed during the Paleozoic, except for the Archean and Proterozoic host rocks intruded by Neoproterozoic dykes in

Kuluketage and the western marginal area of the Tarim Basin. Further classification of host rocks reveals that among the Paleozoic host rocks, the majority formed during the Late Paleozoic.

5 Primary Understanding of Some Mafic Dyke Swarms in Central Asia

5.1 Multi-Period Dykes in the Eastern Tianshan and Beishan

The dykes in these areas are the result of multi-period tectonic events. The most widely distributed dykes intruded during the Late Carboniferous to Early Permian (Liu et al. 1999; Li et al. 2006b; Xiao et al. 2006a; Pirajno et al. 2008; Qin et al. 2011; Su et al. 2011). Some studies have considered that the origination of these dykes is related to LIPs or mantle plumes during that period (Pirajno et al. 2008; Qin et al. 2011; Su et al. 2011); however, in some outcrops the dyke-filled fractures are obviously controlled by regional shearing displacement (Fig. 5a, b). Other dykes sparsely emplaced during intrusion of Mesozoic round-shaped plutons (Li et al. 2002a; Zhang et al. 2006; Wang et al. 2008; Li et al. 2010, 2014; Zhang et al. 2016) are much younger (Fig. 5c), and resulted from intra-continental evolution with weak magmatic activities.

5.2 Permian and Neoproterozoic Dykes in Western Tarim and Kuruktag

A dyke swarm in Keping in the western Tarim (a segment of the passive margin of the Tarim during the Paleozoic), constrained as occurring from 270–290 Ma by volcanic-sedimentary formations (Li et al. 2017a) cut by the dykes, is also related to the Permian Tarim LIP. Besides, some Cenozoic mafic dykes (48–46 Ma) in Piqiang basin, western Tarim, and the dyke-filled fractions are caused by S–N compression (Li et al. 2009a).

The protolith of the Aksu blueschist is a part of the oceanic crust accreted to Tarim as part of an accretionary wedge during the Neoproterozoic. It experienced high-pressure metamorphism (860–870 Ma) during the processes of deep subduction and exhumation (Zhang et al. 2008b; Zheng et al. 2008; Shen and Geng 2012; Zhang et al. 2014). Dozens of NW-SE trending diabase dykes emplaced in the Aksu blueschist, and the widths of the dykes range from several centimeters up to 20 m. The strikes of the dykes are nearly orthogonal to the metamorphic foliations (Fig. 6a, b). Previous chronological work revealed that these dykes occurred during 759–807 Ma (Chen et al. 2004; Zhan et al. 2007; Zhang et al. 2009a). In the Kuruktae area, the dykes are ultra-high-densely emplaced (the highest density of dykes in Central Asia, Fig. 6c,

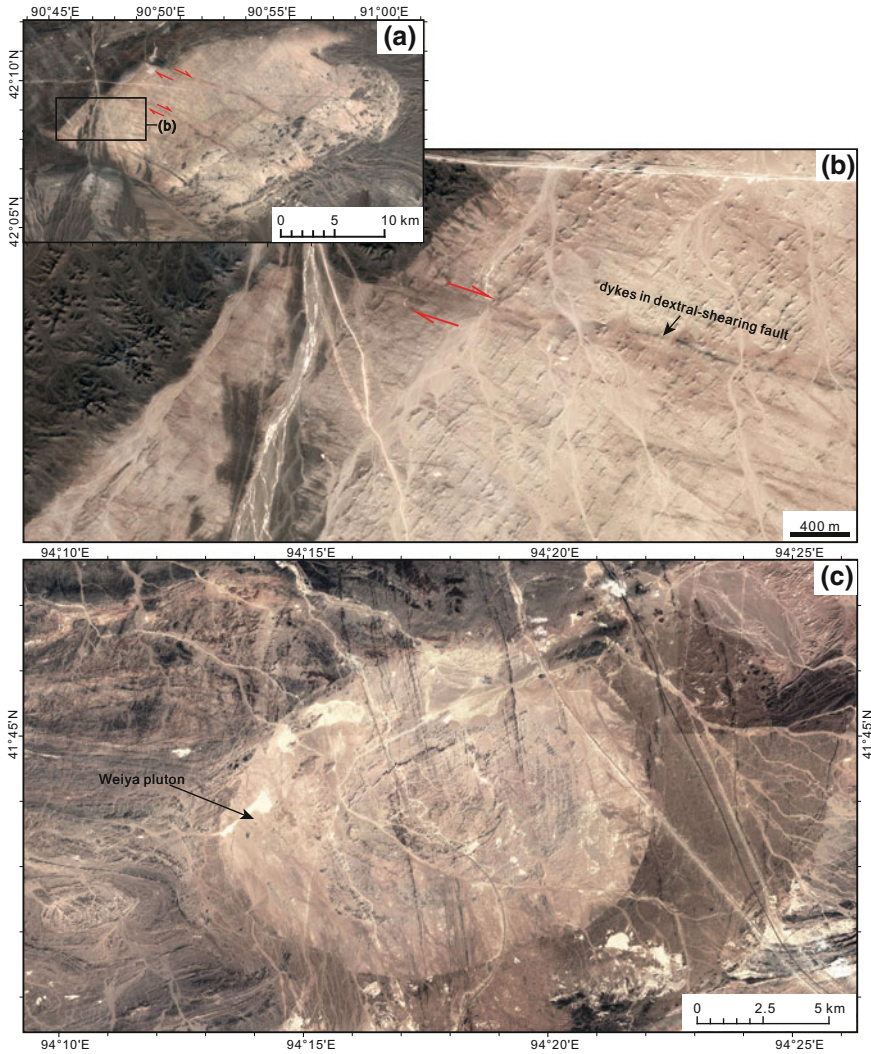


Fig. 5 Some mafic dykes emplaced in Eastern Tianshan **a, b** Dykes intruded in dextral-shearing faults, in a granite pluton. **c** Several NNW-SSE trending dykes emplaced in Mesozoic round-shaped pluton in Weiya area (The images are downloaded from Google Earth)

d), and a notable zebra-like scene occurs in the field (Zhang et al. 2009b). The dykes in Kuruktag were intruded 823 ± 8.7 Ma and 776.8 ± 8.9 Ma, which may record the influence of mantle-originating magma during the break-off of Rodinia (Zhang et al. 2009b).

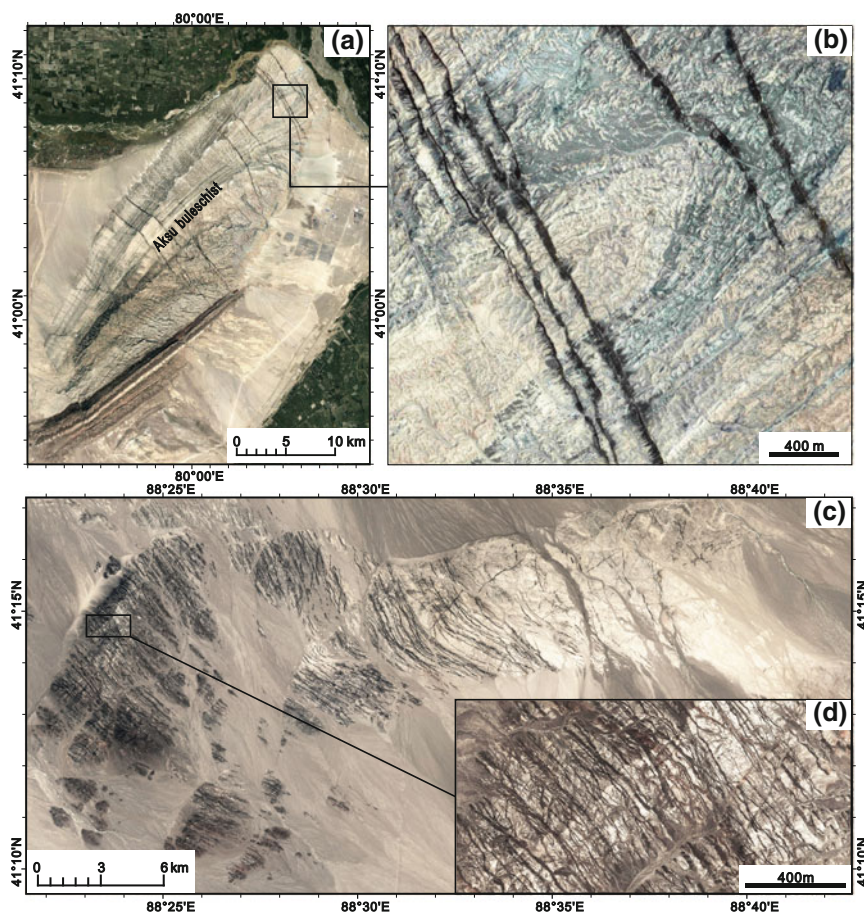


Fig. 6 Mafic dykes emplaced in Aksu buleschist and Kuruktag area **a, b** Dykes emplaced in Aksu buleschist (Western margin of the Tarim) **c, d** Kuruktag (Eastern Tianshan) is the most dyke-concentrated area among the Central Asia.(The images are downloaded from Google Earth)

5.3 Late Paleozoic Dykes in Western Junggar, Eastern Junggar and Chingis-Taerbahatai

Dykes in these areas mostly emplaced during the Late Carboniferous to Early Permian, based on previous chronological studies of dykes in Western Junggar (Li et al. 2004; Xu et al. 2008; Zhou et al. 2008; Feng et al. 2012a, b; Yin et al. 2012; Zhang and Zou 2013), constrained by the cutting relationship between the dykes and the host rocks (plutons and volcanic-sedimentary formations) in Eastern Junggar (Feng et al. 2015) and Chingis-Taerbahatai.

The spatial distribution patterns of dykes are obviously influenced by the NE–SW–trending Darabut fault/suture line in Western Junggar, two NW–SE–trending suture lines (Karamaili and Aermantai) in Eastern Junggar, and the NW–SE–trending suture line in Chingis-Taerbahatai (Han et al. 2010), respectively. Dykes in these areas play an important role in providing more insights regarding subductions and collisions during the Late Paleozoic.

5.4 Paleozoic Dykes in the North and West Bank of Balkhash

The host rocks intruded by the dyke swarms mainly formed during the Paleozoic (more so during the Late Paleozoic and less so during the Early Paleozoic). The spatial and temporal distribution of dyke swarms is coincidentally overlapped by a well-known orocline tectonic belt (composed of a huge C-shaped Paleozoic tectonic belt) in Kazakhstan (Van der Voo et al. 2007; Abrajevitch et al. 2008; Xiao et al. 2010a; Li et al. 2017b). More detailed studies of dykes may more convincingly elaborate on the mechanisms and processes of this orocline (Fig. 7).

5.5 Dykes in Western Mongolian-Altai

The host rocks of the dykes in this area formed during both the Early and Late Paleozoic. The optimal directions of NW–SE and NE–SW in this area are very clear; however, whether this assemblage is representative of conjugate fractures needs more kinematic evidence on smaller scales.

6 Discussions and Conclusions

6.1 Observational Methods of Dyke Swarms at Different Scales

This study only reports the distribution patterns of dyke swarms on a large scale in Central Asia, and provides a framework for more comprehensive dyke-related studies on a regional scale in the future. However, detailed studies in smaller areas (medium scale) and higher resolution images (such as Google Earth images) must be applied. For anatomical study (small to microscopic scale), observation in outcrops and under a microscope must be carried out.

In recent years, the popularity of unmanned aerial vehicles (UAVs) has made low-cost aerial photography a reality. Aerial photos with ultra-high resolution provide a new visual aspect of dykes, which can greatly enhance work efficiency.

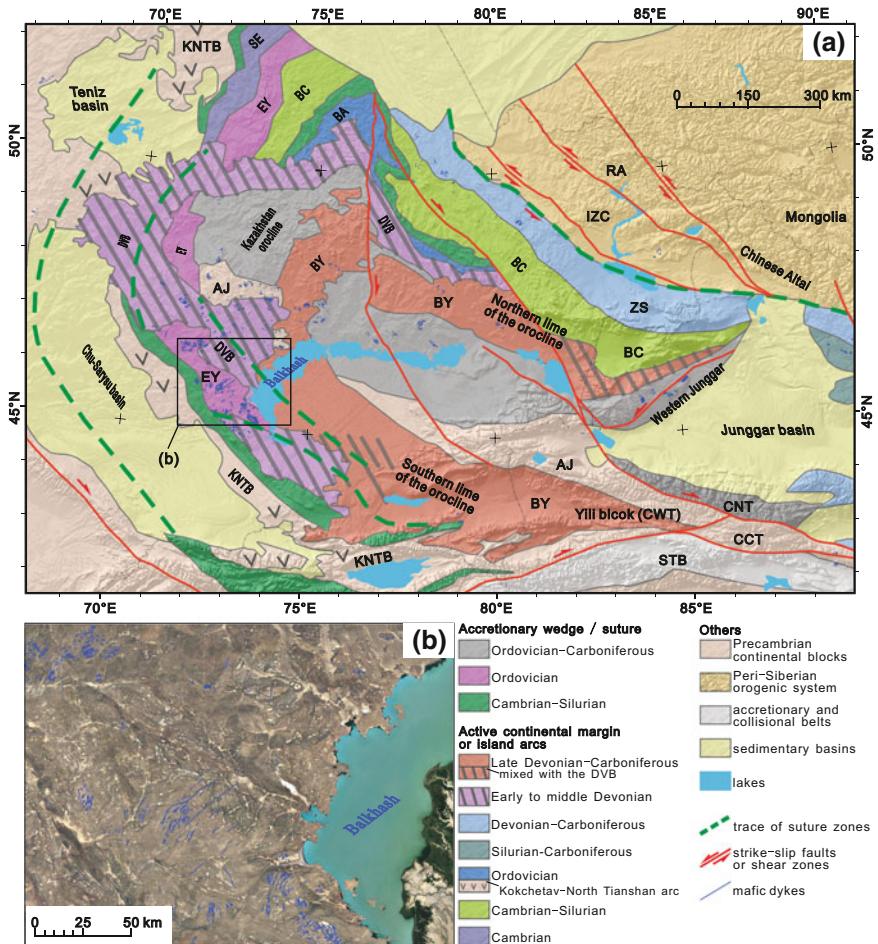


Fig. 7 Spatial relationship of mafic dykes and Kazakhstan orocline. **a** The Kazakhstan orocline and mafic dykes emplaced in Balkhash area. **b** Some dykes emplaced in Western Balkhash (the image is downloaded from Google Earth). The base map of the Kazakhstan orocline is re-made according to Li et al. 2017b. RA: Rudny Altai; IZC:Irtysh-Zaisan complex; ZS: Zharma-Saur arc; BC: Boshchekul-Chingiz arc; BA: Baydaulet-Akbastau arc; EY: Erementau-Yili belt; SE: Selety arc; DA: Dulate arc; YA: Yemaquan arc; BY:Balkhash-Yili arc; DVB: Early to Middle Devonian volcanic belt; KNTB: Kokchetav-North Tianshan belt; IMT: Ishim-Middle Tianshan block; AJ: Aktau-Junggar block; CCT: Chinese central Tianshan block; CNT: Chinese North Tianshan belt; STB: South Tianshan belt; CWT: Chinese western Tianshan

6.2 *Relationship of Spatial Distribution Patterns and Regional Tectonic Evolution*

The large number of mafic dykes exhibited in the present crust of Central Asia are a result of tectonic events including fracturing in the upper crust and rising of magma from the lower crust or even mantle. The spatial-temporal distribution patterns of the mafic dykes are multipurpose records to understand the continental evolution including angles of fracturing processes and related crustal deformation, magma sequences, interaction between crust and mantle, etc.

The density variation of the dykes in space and period reflect the intensity of crustal deformation and magmatic activities during their emplacement. This work reveals that more than 99% of the mafic dykes emplaced in six areas as displayed in Fig. 1b. The majority of the dykes formed during the Late Paleozoic, the exception being the Neoproterozoic dykes that intruded into the metamorphosed basement of the Tarim craton and Kuruktag block.

In the distribution map of the dykes, it can be seen that the reasons for the formation of these mafic dykes are diverse. Most dykes emplaced in marginal areas of major tectonic units (West Junggar, Eastern Junggar, North and West bank of Balkhash, some parts of Eastern Tianshan and Beishan, and Chingis-Taerbahatai) resulted from compression and shearing between contact blocks or extensional fractures caused by subduction-related magma or post-collision-related magma. The Permian dykes in the west marginal area of the Tarim and Eastern Tianshan may be related to an LIP or giant mantle plume beneath the Tarim craton during the Permian. Some Neoproterozoic dykes intruded into the Aksu blueschist complex (exposed metamorphosed basement of the Tarim craton) and Kuruktag block record the break-off of the Tarim craton and Kuruktag block.

For more comprehensive studies of mafic dykes in the future, the geometric-kinematic characteristics of the dyke-filled fractures in the host rocks can be revealed showing evidence of movement and crosscutting and displacement relationships between differently oriented dykes (widespread dextral/sinistral displacement along the strike of dykes hints that most fractures in nature are not caused by extensional stress, but shear or even compressional stress conditions), and boundary surfaces between the dykes and their host rocks. The significance of dyke-related magma could be revealed by testing the dykes using chronological and geochemical methods, as well as correlation of the dykes and host rocks.

Acknowledgements This study was co-supported by the National Natural Science Foundation of China (project number 41502201) and the “Western Light” project of the Chinese Academy of Sciences (project number XBBS201301). We are grateful to Prof. Rajesh Srivastava and Prof. Peng for their thoughtful arrangements. We also thank two reviewers for constructive comments which led to major improvements in the manuscript.

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