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Dyke Swarms of the World: A Modern Perspective

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Preface

Detailed multidisciplinary studies on mafic dyke swarms play a crucial role in solving geodynamic problems of Earth's history. Professor Henry C. Halls recognized the importance of dyke swarms long ago and organized the first International Dyke Conference focusing on geological, geochemical, and geophysical aspects of dykes and related units in Toronto, Canada, in 1985. Given the new insights arising during that conference, it was decided that International Dyke Conferences (IDCs) should be held every 5 years. Consequently, IDC-2 was held in Australia in 1990, IDC-3 in Israel in 1995, IDC-4 in South Africa in 2001, IDC-5 in Finland in 2005, and IDC-6 in India in 2010. Each IDC also produced a proceedings volume (apart from IDC-4 whose contributions were published as part of the IDC-5 volume) (Halls and Fahrig 1987; Parker et al. 1990; Baer and Heimann 1995; Hanski et al. 2006; Srivastava 2011).

Continuing the tradition, the Seventh International Dyke Conference (IDC-7) was hosted by the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, and held on August 18–20, 2016, at the Friendship Hotel in Beijing. Approximately, 140 dyke researchers from 19 countries attended this conference which had the theme "Dyke Swarms: Keys to Paleogeographic Reconstruction," which was further divided into 10 sub-themes to cover almost every aspect of modern research on dykes and related units:

1. Regional maps/reviews of dyke swarms and related units
2. The role of giant dyke swarms in the reconstruction of supercontinents/paleocontinents: progress, problems, and potential
3. Mapping of dykes using remote-sensing techniques: aeromagnetic data, Landsat, radar, etc.
4. Geochronology of dyke swarms
5. Petrology, geochemistry, and petrogenesis of dykes
6. Emplacement mechanism of dykes
7. Dyke swarms on planetary bodies

8. Links to mineralization and resources
9. Miscellaneous: synplutonic mafic dykes and alkaline dykes, etc.
10. Oceanic dyke complexes: seafloor spreading, oceanic plateaus, or juvenile arcs?

An abstract volume (containing 133 abstracts) was provided at the conference, and these abstracts were subsequently published in Acta Geologica Sinica (Peng et al. 2016).

Group photograph of the IDC-7 participants

As a tradition of IDCs, it is customary to publish a volume based mainly on presentations during the conference but also including additional key research on dykes. The large volume of abstracts at IDC-7 and the varied themes led to the planning of two volumes. The first one, titled "Dyke Swarms: Keys for Precambrian Paleogeographic Reconstruction," will be published as a special issue of Precambrian Research (Editors: Peng Peng, Richard E. Ernst, Ulf Söderlund, and Michael Hamilton), and the second one is this volume. Originally, about 30 participants expressed interest to submit their work to this volume. Ultimately, 15 manuscripts were received and reviewed. All the submitted manuscripts were reviewed by at least two reviewers, in addition to reviews from the guest editors. Thirteen manuscripts were accepted for this volume. A brief description of each contribution is presented below.

It is well established that mafic dyke swarms in shield areas provide the most complete record of short-lived, mantle-generated large igneous province (LIP) events through time and space, which provides valuable information on geodynamics, locating mantle plume centers, evolution of the mantle, paleogeographic reconstructions, links with metallogeny, and links to climate change including mass extinction events (e.g., Halls 1982; Halls and Fahrig 1987; Parker et al. 1990; Baer and Heimann 1995; Hanski et al. 2006; Srivastava 2011; Ernst 2014; Ernst and Jowitt 2013, 2017; Ernst and Youbi 2017). Therefore, systematic study and information on mafic dyke swarms can be very useful for solving many geological problems as illustrated in this volume.

The volume starts with two review chapters: Chapter “Giant Circumferential Dyke Swarms: Catalogue and Characteristics” on the giant circumferential dyke swarms (**Buchan and Ernst**) and Chapter “Magma Transport Pathways in Large Igneous Provinces: Lessons from Combining Field Observations and Seismic Reflection Data” on using seismic reflection data to understand magma plumbing systems (**Magee et al.**). A dominant feature of LIP plumbing systems is their regional radiating mafic dyke swarms usually interpreted to focus on the center of a mantle plume responsible for the LIP (e.g., Halls 1982; Ernst and Buchan 1997, 2001; Ernst 2014). However, a new class of giant swarms is now recognized, termed giant circumferential swarms which with a circular or elliptical geometry (Ernst and Buchan 1998; Buchan and Ernst 2018). **Buchan and Ernst** (Chapter “Giant Circumferential Dyke Swarms: Catalogue and Characteristics”) provide a comprehensive catalogue and characteristics of giant circumferential dyke swarms from around the world (most newly recognized and presented here for the first time). Most of these appear to be linked to giant radiating dyke swarms, LIPs, and mantle plumes. A comparison is made between these identified terrestrial examples and possible analogues on Venus (coronae) and Mars.

Magee et al. (Chapter “Magma Transport Pathways in Large Igneous Provinces: Lessons from Combining Field Observations and Seismic Reflection Data”) present seismic reflection data on sill complexes and dyke swarms in order to better constrain their structure and emplacement. This review provides insights into the connectivity of and magma flow pathways within extensive sill complexes and how sill complexes are spatially accommodated. This work also reveals changes in dyke width with height and how dyke-induced normal faults and pit chain craters can be used to locate sub-vertical dykes offshore. These observations provide insights into properties of LIP magma plumbing systems both on Earth and other planetary bodies.

Hollanda et al. (Chapter “The Mesozoic Equatorial Atlantic Magmatic Province (EQUAMP)”) provide ^{40}Ar/^{39}Ar ages, geochemical and airborne magnetic data on mafic dyke swarms and sills belonging to the Equatorial Atlantic Magmatic Province (EQUAMP), a newly identified early Cretaceous ~135–120 Ma LIP in South America. They suggest that the Rio Ceará Mirim dykes (which can now be traced for over 1000 km along an arcuate trajectory) and Sardinha sills are derived from melting of a subcontinental lithospheric mantle source.

Teixeira et al. (Chapter “Intraplate Proterozoic Magmatism in the Amazonian Craton Reviewed: Geochronology, Crustal Tectonics and Global Barcode Matches”) provide a detailed evaluation of geochronology (including U–Pb baddeleyite ages) and geochemistry of the Proterozoic mafic dyke swarms and sills of the Amazonian Craton. Such data are provided for a number of LIPs/SLIPs (silicic LIPs) that include the major Orocaima (1.98–1.96 Ga), Uatumã (1.89–1.87 Ga), Avanavero (1.79 Ga), and the Rincón del Tigre–Huanchaca (1.11 Ga) events. Other magmatic events are reported from the Central Brazil and Guiana shields, for example the Mata-Matá (1.57 Ga), Salto do Céu (1.44 Ga), and Nova Floresta (1.22 Ga) mafic sills and the

Cachoeira Seca troctolite dykes and laccoliths (1.19 Ga). Petrogenesis and paleogeographic reconstruction of all these LIPs/SLIPs are also discussed, and the authors suggest that the Proterozoic intracratonic LIP/SLIP events were part of the breakup of the Columbia supercontinent.

The next three chapters focus on dyke swarms and their associated LIPs from the African shield. The first of these, **de Kock et al.** (Chapter "The Precambrian Mafic Magmatic Record, Including Large Igneous Provinces of the Kalahari Craton and Its Constituents: A Paleogeographic Review"), is a review of the Precambrian mafic magmatic record of the Kalahari Craton. They summarized the available precise U–Pb crystallization ages and paleopoles of mafic rocks with a particular focus on reclassification of the mafic dyke swarms, identification of LIPs, and implications for paleogeographic reconstructions. They also identified gaps in our knowledge of the Precambrian mafic record of the Kalahari Craton to be filled by multidisciplinary studies combining the latest advances in U–Pb geochronology along with both paleomagnetism and geochemistry.

Wabo et al. (Chapter "Constraining the Chronology of the Mashishing Dykes from the Eastern Kaapvaal Craton in South Africa") provide new geochronological, geochemical, and paleomagnetic data for NNE-trending dykes near Mashishing in the eastern Kaapvaal Craton. These data indicate that these Mashishing dykes belong to four different events: (i) a ~2.25–2.20 Ga pre-Bushveld dyke swarm, (ii) a dyke related to the ~2.06 Ga Dullstroom Lavas (part of the Bushveld LIP), (iii) the ~1.87–1.83 Ga Back Hills dyke swarm, and (iv) the ~1.11 Ga Umkondo dyke swarm.

Baratoux et al. (Chapter "New U–Pb Baddeleyite Ages of Mafic Dyke Swarms of the West African and Amazonian Cratons: Implication for Their Configuration in Supercontinents Through Time") present 14 new high precision new U–Pb TIMS ages ranging between 1790 and 200 Ma from doleritic dykes in the southern part of the West African Craton. The following swarms are distinguished: 1791 Ma N010° trending Libiri, 1764 Ma N035° trending Kédougou, 1575 Ma N100° trending Korsimoro, ~1525–1529 Ma N130° trending Essakane, 915 Ma N070° trending Oda, ~870 Ma N355° trending Manso, and 202 Ma N040° trending Hounde swarm, and also a 200 Ma for the mafic sills in the Taoudeni basin. All these Proterozoic swarms were previously unknown, this chapter provides the first robust LIP bar code for the southern West African Craton, and the results are used in a new paleogeographic Proterozoic reconstruction. The newly discovered 200 Ma Hounde swarm has trend oblique to the previously recognized giant radiating swarm of the CAMP LIP.

Central Asia is a major part of the Asian–European continent and occupies most of the western Central Asian Orogenic Belt. **Feng et al.** (Chapter "Spatial and Temporal Distribution Patterns of Mafic Dyke Swarms in Central Asia: Results from Remote-Sensing Interpretation and Regional Geology") present spatial–temporal distribution patterns of the mafic dyke swarms on the basis of detailed mapping with the help of remote-sensing interpretation and regional geology. The majority of these mafic dykes were emplaced in the Eastern Tianshan and Beishan, Western Mongolian Altai, Eastern Junggar, North and West Bank of Balkhash, Western Junggar, and Chingis-Taerbahatai regions.

Samal et al. (Chapter "Neoarchean-Mesoproterozoic Mafic Dyke Swarms of the Indian Shield Mapped Using Google Earth™ Images and ArcGIS™, and Links with Large Igneous Provinces") present a comprehensive study of the Neoarchean–Mesoproterozoic mafic dyke swarms of the Indian Shield including mapping them using Google Earth™ images and ArcGIS™. They identify 24 Neoarchean–Mesoproterozoic mafic dyke swarms, which belong to 14 distinct mafic magmatic events in the Indian Shield (Dharwar, Bastar, Singhbhum, Bundelkhand, and Aravalli Cratons) and suggested that these swarms represent the exposed plumbing system for large igneous provinces (LIPs). This work also suggests a connection of the Indian Shield with Kenorland/Superia ($\sim$2.75–2.07 Ga), Columbia/Nuna (1.90–1.38 Ga), and Rodinia (1.20–0.72 Ga) supercontinents. They note that additional U–Pb geochronology and associated paleomagnetism are required to fully constrain the timing and pattern of the assembly of the various Indian Cratons and any post-assembly rotations between these cratons.

Sesha Sai et al. (Chapter "Petrology and Mineral Chemistry of a Porphyritic Mafic Dyke, Jonnagiri Schist Belt, Eastern Dharwar Craton, India: Implications for Its Magmatic Origin") share petrological and mineral chemistry of a Paleoproterozoic porphyritic mafic dyke from the eastern Dharwar craton, India. They estimated temperature and oxygen fugacity for the coexisting magnetite–ilmenite solid solution pairs which yielded an equilibration temperature of $\sim$756 °C and $10^{-15.6}$ atm f_{O_2}.

Proterozoic mafic dykes from the Bomdila area, NE Lesser Himalaya, India, have been studied for geochemical characteristics and petrogenesis and tectonic significance (**Rashid et al.**) (Chapter "Geochemistry, Petrogenesis and Tectonic Significance of the Proterozoic Mafic Dykes from the Bomdila Area, NE Lesser Himalaya, India"). Geochemistry of these intrusive mafic rocks suggests their derivation from an enriched lithospheric mantle source (rather than being affected by crustal contamination) and emplacement in a continental rift tectonic environment.

Torkian (Chapter "Petrology and Tectonic Setting of Dyke Swarms Emplaced in the Upper Jurassic Qorveh Granitoid Complex (Majidaba and Kangareh), Kurdistan Province, Iran") discusses petrological characteristics of mafic dykes from the Kurdistan Province, Iran. These mafic rocks show a tholeiitic to calc-alkaline nature and probable emplacement in an active continental margin tectonic setting.

The final Chapter "From Ophiolites to Oceanic Crust: Sheeted Dike Complexes and Seafloor Spreading" is focused on sheeted dyke complexes (**Karson**). He has provided a thorough review of sheeted dyke complexes in ophiolites and also includes sheeted dike complexes on the seafloor. He demonstrates how sheeted dyke complexes are key to understanding the fundamentals of the tectonics, magma plumbing networks, and hydrothermal/biological systems at mid-ocean ridges.

This IDC-7 volume demonstrates significant progress since the last dyke conference (IDC-6 in India in 2010) and shows that the field of dyke swarm research remains rich in research ideas. This volume is also an acknowledgment of the vision of Henry Halls who launched the field of modern dyke swarm studies with Halls (1982) and IDC-1 in 1985 (Halls and Fahrig 1987). Current research foci include mafic dyke swarms associated with LIPs, with ophiolites, and on planetary bodies, and also the implications for the continental breakup, climate change, and resource exploration. These research areas remain important, but going forward there is also opportunity in addressing: mafic dyke swarms in arc systems, and also addressing silicic and kimberlite dyke swarms.

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Contents

Giant Circumferential Dyke Swarms: Catalogue and Characteristics

Kenneth L. Buchan and Richard E. Ernst

Abstract Giant circumferential dyke swarms have a primary geometry that is quasi-circular or quasi-elliptical. Examples and possible examples described previously or identified in this study have outer diameters that range from ~450 to ~2500 km. There has been little study of these features. Here, we present a global catalogue of giant circumferential dyke swarms and discuss their characteristics. All of the identified giant circumferential swarms are of mafic composition. Many, but not all, are associated with a roughly coeval giant radiating dyke swarm whose focus is at or near the centre of the circumferential system. As giant radiating swarms are usually interpreted to focus above mantle plume centres and form a key component of the plumbing system of large igneous provinces (LIPs), it is likely that giant circumferential swarms linked to radiating systems are also plume and LIP related. The largest giant circumferential swarms have diameters comparable to the diameters postulated for the flattened heads of plumes that have risen from the core-mantle boundary, suggesting that they may be associated with the outer edge of a flattening or flattened mantle plume head. Smaller giant circumferential swarms could be linked with small plumes from the mid-mantle or with the edge of a magmatic underplate above a plume head. Giant circumferential dyke swarms on Earth may be analogues of coronae on Venus and similar features on Mars. Coronae are large tectono-magmatic features that typically consist of a quasi-circular or quasi-elliptical graben-fissure system and associated topography (central uplift or depression, and circular rim or

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moat). In some instances, they are linked to a giant radiating graben-fissure system and LIP-scale volcanism. Both radiating and circumferential graben on Venus and Mars have been interpreted to be underlain by dykes.

Keywords Giant circumferential dyke swarm · Giant radiating dyke swarm
Large igneous province · Mantle plume · Corona

1 Introduction

Giant radiating dyke swarms, which are mainly of mafic composition, are an important component of the plumbing systems of large igneous provinces (LIPs). They are usually thought to be emplaced from a focal region above a mantle plume (e.g., Halls 1982; Ernst and Buchan 1997, 2001), mainly because of their large scale, radiating geometry, evidence for lateral flow and the presence in many cases of an associated domal uplift. Several authors, however, support alternative models, such as those in which radiating dyke swarms form as a result of plate tectonic processes (e.g., McHone et al. 2005). For example, dykes could conceivably be emplaced into fanning fracture systems that develop as the result of indentor-style plate convergence, or could be emplaced vertically along the arms of radially oriented rift systems without an associated plume.

Ernst and Buchan (1998, 2001) identified three large mafic dyke swarms with a circular or elliptical geometry associated with the 250 Ma Siberian Traps, 1110–1185 Ma Keweenawan (North America) and ca. 980–930 Ma Rogaland (Scandinavia) magmatic events, and proposed that they may circumscribe mantle plume centres. They further suggested that such circumferential swarms may be eroded versions of tectono-magmatic structures, called coronae, on Venus. Coronae usually exhibit a quasi-circular or quasi-elliptical annulus of graben and fissures, volcanics (sometimes of LIP-scale) and topographic features such as a central uplift, central depression, uplifted rim or moat (e.g., Stofan et al. 1992). However, in some cases the geometry of coronae is more complicated. Occasionally, the annulus is characterized by compressional structures termed wrinkle ridges.

Giant circumferential dyke swarms are large swarms with a primary geometry that is quasi-circular or quasi-elliptical. Examples and possible examples that are catalogued in this study have diameters that range from ~450 to ~2500 km.

It should be noted that some giant dyke swarms have an arcuate pattern as the result of secondary deformation, or as the result of deflection from a linear or radiating geometry in the presence of a regional stress field (Ernst et al. 1995). Such swarms are not considered to be giant circumferential swarms.

A number of the catalogued giant circumferential swarm are centred near the focus of a roughly coeval giant radiating swarm. Assuming that the radiating swarm is linked to a mantle plume, then it is likely that the circumferential swarm is also linked to the same plume. However, other giant circumferential swarms, without an associated radiating swarm, may or may not be plume related.

In addition to giant circumferential swarms that are the subject of this study, there are much smaller circumferential swarms with diameters that range from a few kilometres to several tens of kilometres or more. The intrusions of these swarms are usually referred to as ring dykes if vertical or outward dipping, and cone sheets if inward dipping (e.g., Neuendorf et al. 2005). They are found in a variety of setting. Examples include circumferential swarms related to active volcanoes of the Galapagos Islands (Chadwick and Howard 1991; Chadwick et al. 2011) and the active Niuafo'ou volcano in a back-arc basin setting behind the Tonga Arc (Newhall and Dzurisin 1988), circumferential swarms within and around the margins of the central igneous complexes (deeply eroded roots of large volcanoes) of the 65 Ma British Tertiary Igneous Province of the North Atlantic LIP (Emeleus 1982; Burchardt et al. 2013), the 65 km diameter Meugueur-Meugueur troctolite ring dyke/cone sheet of northwestern Africa (Moreau et al. 1995), and the circumferential dyke swarm on the periphery of the deformed, late Archean Blake River Group megacaldera complex of North America with an original diameter of 80–90 km (Pearson and Daigneault 2009).

Since the original identification of giant circumferential dyke swarms by Ernst and Buchan (1998), further examples have been described in the literature. Mäkitie et al. (2014), and Ruotoistenmäki (2014) described a ca. 1380 Ma giant circumferential swarm at Lake Victoria in Africa which is linked to the Kunene-Kibaran LIP (Mäkitie et al. 2014; Ernst 2014; Buchan and Ernst 2016). Buchan and Ernst (2018) reconstructed a giant circumferential dyke swarm related to the ca. 135–75 Ma High Arctic LIP (HALIP).

In addition, there are some studies where it has been suggested that individual dykes or small dyke swarms, which are too short to display an arcuate pattern but are oriented perpendicular to a roughly coeval giant radiating dyke swarm, may be part of a giant circumferential system. Pehrsson et al. (1993) described an example in which a 1267 ± 3 Ma (U-Pb) dyke, located within and parallel to the Great Slave Lake shear zone along the southern margin of the Slave craton, is oriented perpendicular to the coeval Mackenzie giant radiating dyke swarm of North America, and is located ~1000 km from the swarm focus. Denyszyn et al. (2009) proposed that the ~150 km long 713–716 Ma (U-Pb) Clarence Head dyke swarm of North America, which is slightly younger than and crosscuts the ca. 720 Ma Franklin giant radiating dyke swarm at right angles ~1250 km from the swarm focus, may represent a segment of a giant circumferential system. In the discussion that follows we only include the cases where a swarm of dykes (e.g., Clarence Head swarm), rather than individual dykes, has been identified perpendicular to a radiating swarm.

In this paper, we catalogue and briefly describe the giant circumferential dyke swarms and possible segments of circumferential swarms that have been reported to date from around the globe, and identify a number of additional examples. The additional examples include swarms associated with the 65 Ma Deccan (India) and 135–120 Ma Paraná-Etendeka (South America and Africa) LIPs, and possible swarms linked to the 62–54 Ma North Atlantic, ca. 92–88 Ma Madagascar (Madagascar and India), ca. 183 Ma Karoo (Africa), ca. 370 Ma Yakutsk-Vilyui (Siberia), ca. 1110 Ma Umkondo (Africa), ca. 1210 Ma Marnda Moorn (Australia) and ca. 1780 Ma

Xiong'er-Taihang (northern China) magmatic events. We briefly summarize the characteristics of giant circumferential swarms and compare these characteristics with those of coronae on Venus and similar structures on Mars.

It is hoped that our catalogue of giant circumferential swarms and the preliminary analysis of their characteristics herein will stimulate further studies to identify addition examples and to better understand these little-known features.

2 Global Catalogue of Giant Circumferential Dyke Swarms

Giant circumferential dyke swarms and possible swarms or swarm segments are listed by age in Table 1, along with basic characteristics including outer diameter, arc length, width and the presence or absence of a coeval radiating swarm. It should be noted that all of the identified swarms are entirely or almost entirely of mafic composition. One example of a possible circumferential system of wrinkle ridges is also included. The global distribution of giant circumferential systems is illustrated in Fig. 1. Each swarm is briefly described below.

2.1 Giant Circumferential Dyke Swarms

Dykes of Deccan LIP, India (ca. 67–65 Ma): Dykes of the ca. 67–65 Ma (Renne et al. 2015; Schoene et al. 2015) Deccan LIP are summarized in Fig. 2. The best defined and described dykes form dense subswarms parallel to the ENE-trending Narmada-Tapi and S-trending West Coast rift systems (e.g., Bondre et al. 2006; Vanderkluysen et al. 2011). Dyke orientations in the region between these subswarms are more complicated and have variously been described as random (Hooper 1990) or, in some areas, as having a dominant NE trend (e.g., Bondre et al. 2006). Vanderkluysen et al. (2011) analysed dyke trends and geochemistry, and concluded that lower portions of the Deccan lava pile were likely fed by the ENE- and S-trending dykes, whereas upper portions were fed by the dykes without a preferred orientation. Dykes in more northern regions of the Deccan LIP are less well studied.

We interpret the Narmada-Tapi and West Coast subswarms as part of a giant radiating swarm (cf. Ernst and Buchan 1997), along with dykes that trend NW across the Saurashtra (Kathiawar) region (Auden 1949). A sparse set of dykes has been mapped at approximately right angles to each of these radiating subswarms (e.g., Clark 1880; Auden 1949; Sant and Karanth 1990; Dessai and Viegas 1995; Ray et al. 2007). In the Saurashtra region the dykes that intersect the radiating subswarm display an arcuate pattern as described by Auden (1949). We interpret the dykes that are perpendicular to the subswarms of the radiating system, including the arcuate dykes of Saurashtra, and the NE dykes located between the Narmada-Tapi and West Coast subswarms, as part of a giant circumferential dyke swarm with an outer diameter of >600 km and an arc of ~220° (Fig. 2). The centre of the proposed circumferential

Table 1 Catalogue of giant circumferential dyke swarms and possible segments of giant circumferential swarms

Name of event/swarm	Age (Ma)	Outer diameter (km)	Arc (°)	Width[a] (km)	Associated radiating swarm	References
Giant circumferential swarms						
Deccan LIP (India)	ca. 67–65	620	220	200	Yes	Herein
High Arctic LIP (Franz Josef Land, Svalbard, Greenland, N. America)	135–75	1600	220	300	Yes	Buchan and Ernst (2015, 2017, 2018)
Paraná-Etendeka (S. America, Africa)	135–120	1000	130	250	Yes	Herein
Kochikha swarm of Siberian Traps LIP (Siberia)	250	600–300 (ellipse)	~150	130	Yes	Ernst and Buchan (1998, 2001)
Blekinge-Dalarna swarm (Scandinavia)	978–946	1100	70	≥100	?	Ernst and Buchan (1998), Buchan and Ernst (2016)
Keweenawan LIP (N. America)	1110–1085	700–530 (ellipse)	140	≥50	?	Ernst and Buchan (1998)
Lake Victoria swarm of Kunene-Kibaran LIP (Africa)	ca. 1370	650	160	140	No	Mätikie et al. (2014), Ruotoistenmäki (2014), Ernst et al. (2014)
Possible giant circumferential swarms and swarm segments[b]						
British-Irish portion of North Atlantic LIP (Britain, Ireland)	62–54	≥1700	–	≥150?	Yes	Herein
Madagascar LIP (Madagascar, India)	92–88	~2400	70?	450	Yes	Herein

(continued)

Table 1 (continued)

Name of event/swarm	Age (Ma)	Outer diameter (km)	Arc (°)	Width[a] (km)	Associated radiating swarm	References
Karoo LIP (Africa)	183	460	300?	120	?	Chevallier and Woodford (1999), Chevallier et al. (2001), herein
Yakutsk-Vilyui LIP (Siberia)	380–360	1600	150?	300?	Yes	Herein
Clarence Head swarm of Franklin LIP (N. America)	716–713	~2500	–	≥70	Yes	Denyszyn et al. (2009)
Umkondo LIP (Africa)	ca. 1110	2300	–	70	Yes	Herein
Marnda Moorn LIP (Australia)	ca. 1210	1040	90 (N) 100 (S)	250	?	Wang et al. (2014), herein
Lüliang swarm of Xiong'er-Taihang LIP (China)	ca. 1780	1200	–	350	Yes	Peng (2015), Buchan and Ernst (2016)
Circumferential wrinkle ridges						
Yakima folds of Columbia River LIP (N. America)	17	1200–1400	–	≥150	Yes	Mège and Ernst (2001)

[a] Width of a circumferential dyke swarm refers to the distance between the inner and outer diameters of the swarm

[b] Includes cases where dyke distributions are somewhat complicated or dating is not yet sufficient to confirm that all proposed circumferential dykes are of similar age, as well as cases where short swarm segments are both coeval with and perpendicular to a radiating swarm

swarm is near the focus of the radiating swarm in the Gulf of Cambay and falls along the Réunion mantle plume track (Misra et al. 2014).

In some areas the radiating dykes are observed to crosscut the circumferential dykes (e.g., Krishnamurthy 1972; Dessai and Viegas 1995), whereas in other areas the opposite relationship is reported (e.g., Krishnamacharlu 1972). This suggests multiple pulses of circumferential and/or radiating dyke emplacement. Precise radio-

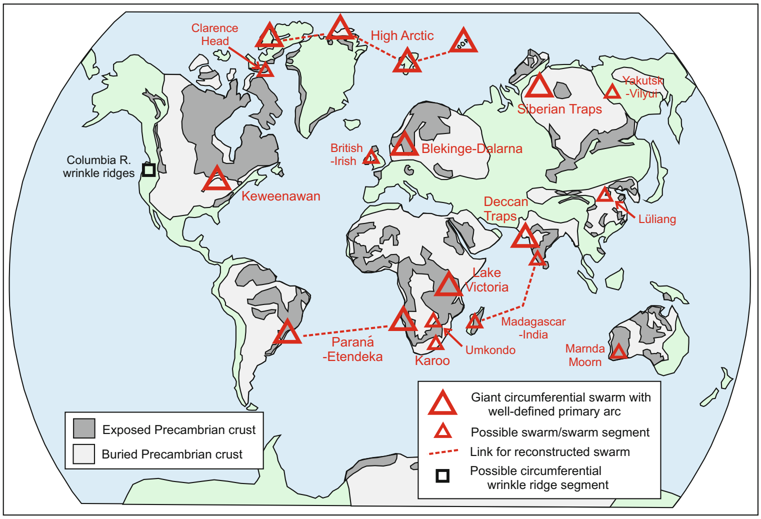

Fig. 1 Global distribution of giant circumferential dyke swarms and possible segments of giant circumferential dyke swarms. Characteristics of each are listed in Table 1 and discussed in the text. Possible compressional wrinkle ridges associated with the Columbia River LIP of North America are also shown. The geological background is modified after Goodwin (1996)

metric dating of the circumferential and radiating dykes from the various regions is needed to clarify the relative ages of the two systems.

Dykes of High Arctic LIP (HALIP), Canadian Arctic islands, northern Greenland, Svalbard and Franz Josef Land (135–75 Ma): Maher (2001) and Buchan and Ernst (2006) described a giant radiating dyke swarm associated with the High Arctic LIP in a reconstruction of the high Arctic region. Buchan and Ernst (2015, 2017) identified a HALIP giant circumferential dyke swarm using the reconstruction of the radiating swarm. Buchan and Ernst (2018) have utilized a more up-to-date reconstruction of the Arctic region to refine the geometry of the circumferential swarm (Fig. 3). The reconstruction involves closing the Eurasia Basin and Baffin Bay (following the reconstruction of Gion et al. 2017), and undoing deformation of the Eurekan orogeny in the eastern Queen Elizabeth Islands of northern Canada based on the radiating dyke pattern and paleomagnetic constraints. Both radiating (black) and circumferential (red) dykes of Fig. 3 are located in each of the four separate regions of the high Arctic that are involved in the reconstruction. The radiating swarm consists of the Queen Elizabeth Islands dykes, the Erlandsen Land dykes of northern Greenland and unnamed dykes of Svalbard and Franz Josef Land, as well as associated aeromagnetic anomalies in the four regions. The circumferential swarm comprises the Surprise Fiord dykes of the Queen Elizabeth Islands, the J. P. Koch dykes of northern Greenland, and unnamed dykes of Svalbard and Franz Josef Land. In the reconstruction of Buchan and Ernst (2018), the circumferential swarm has a roughly circular geometry, an outer diameter of 1600 km, an arc of 220° and a centre that is

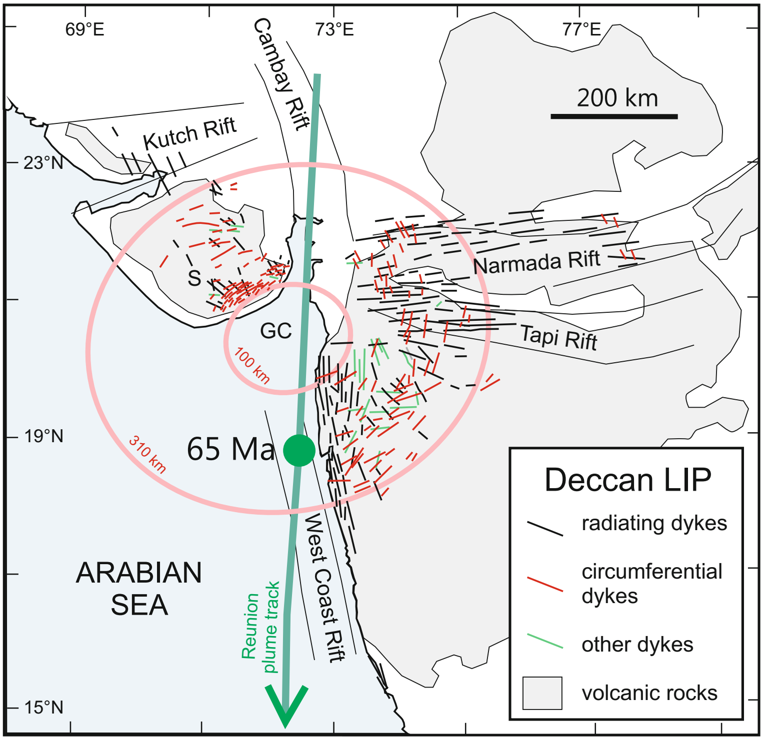

Fig. 2 Circumferential (red) and radiating (black) dykes of the ca. 65 Ma Deccan LIP, India, as described in the text. Dykes of other trends are green. The radiating dykes in the vicinity of the Narmada-Tapi and West Coast rift systems are dense, and have been thinned on the figure for the sake of clarity. Pink circles indicate the approximate outer and inner dimensions of the circumferential swarm. The centre of the circumferential swarm and the focus of the radiating swarm are similar and fall roughly on the (green) Reunion plume track (from Misra et al. 2014). S = Saurashtra (Kathiawar) region; GC = Gulf of Cambay

near, and perhaps slightly offset from, the focus of the radiating swarm. The ages of the circumferential and radiating swarms are poorly constrained. Only a single U-Pb age of 95 ± 1 Ma is available from the radiating swarm, from a probable dyke in the Queen Elizabeth Islands (Kingsbury et al. 2018). Ar–Ar ages of uncertain reliability range between 128 and 86 Ma, and may indicate multiple pulses of radiating dyke emplacement (see summary in Buchan and Ernst 2018). Only a single U-Pb age of 82 ± 2 Ma (Thórarinsson et al. 2015) and a single Ar–Ar age of 82 ± 1 Ma (Kontak et al. 2001), both from northern Greenland, are available from the circumferential swarm, so that it is not possible to speculate on the age span of the overall swarm. However, in Franz Josef Land, proposed circumferential dykes both crosscut and are cut by radiating dykes (Dibner 1998), suggesting that there may have been multiple pulses of circumferential and/or radiating dyke emplacement. HALIP-related topography (summarized in Maher 2001) in the vicinity of the circumferential swarm

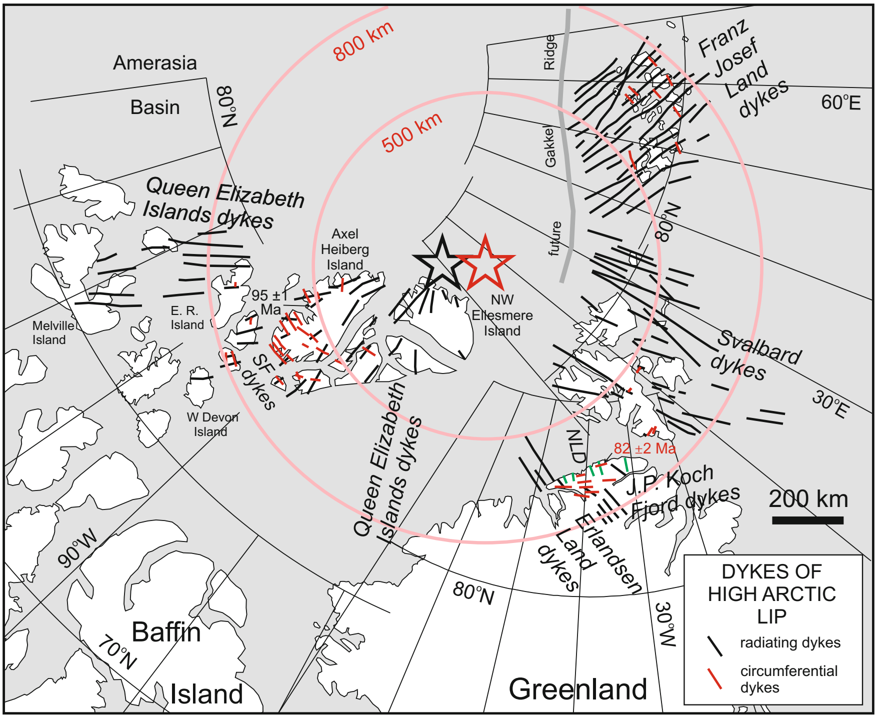

Fig. 3 Circumferential (red) and radiating (black) dykes of the reconstructed 135–75 Ma High Arctic LIP (HALIP) of the Canadian Arctic islands, northern Greenland, Svalbard and Franz Josef Land (modified after Buchan and Ernst 2018). The radiating swarm is dense in some areas, and has been thinned on the figure for clarity. The reconstruction is based on closing the Eurasia Basin, which opened in the Paleogene along the Gakkel Ridge, and Baffin Bay (following Gion et al. 2017), and undoing deformation in the Queen Elizabeth Islands (as described by Buchan and Ernst 2018). Pink circles indicate the approximate outer and inner dimensions of the circumferential swarm. The red star is the centre of the circumferential swarm. The black star is the focus of the radiating swarm. U-Pb ages for a circumferential dyke (Thórarinsson et al. 2015) and a probable radiating dyke (Kingsbury et al. 2018) are indicated with red and black lettering respectively. SF dykes = Surprise Fiord dykes; E.R. Island = Ellef Ringnes Island; NLD = Nansen Land dykes. Nansen Land dykes form a dense N-trending swarm along the northern Greenland coast. They are coloured green, as they may not be part of the HALIP radiating swarm, but rather may be related to rifting that led to the opening of the Eurasia Basin (e.g., Thórarinsson et al. 2015). In addition, although a U-Pb age of 81 Ma has been reported for these dykes (Thórarinsson et al. 2015), paleomagnetic data suggests that some Nansen Land dykes may be Early Carboniferous rather than Cretaceous in age (Abrahamsen et al. 1997)

on Franz Joseph Land and Svalbard could be related to the edge of a domal uplift associated with plume arrival (Maher 2001), or perhaps with a circular uplifted rim (Buchan and Ernst 2018) that is typical of many Venusian coronae.

Dykes of Paraná-Etendeka LIP, Brazil and Namibia (135–120 Ma): Radiating dykes of the Paraná-Etendeka LIP form prominent subswarms that display a triple junction pattern in a pre-drift reconstruction of South America and Africa (Fig. 4; Fig. 1 of Renne et al. 1996; Ernst and Buchan 1997). In South America, the Ponta Grossa subswarm strikes inland perpendicular to the Brazilian coast. To the north and south are the coast-parallel Santos-Rio de Janeiro and Florianópolis subswarms, respectively. In Africa, the coast-parallel Etendeka dykes of Namibia appear to be the counterpart of the Florianópolis subswarm. Numerous maps of local and regional portions of these radiating subswarms show sparse sets of Paraná-Etendeka dykes that intersect the subswarms at approximately right angles (e.g., Figs. 1 and 3b of Sial et al. 1987; Fig. 2 of Raposo 1997; Figs. 2 and 3 of Ewart et al. 2004; Fig. 2 of Guedes et al. 2005; Fig. 4U of Coutinho 2008). We interpret the dykes that intersect the radiating swarm (Fig. 4) as forming a giant circumferential swarm with an outer diameter of ~1000 km. The continental reconstruction of Torsvik et al. (2009), utilized in Fig. 4, brings the proposed circumferential dykes of Brazil and Namibia into alignment. In this reconstruction, the circumferential swarm shares a common centre with the giant radiating swarm.

U-Pb ages for Paraná-Etendeka rocks are sparse. Ar–Ar ages are more numerous. However, the reliability of many of the Ar–Ar ages has been questioned based on the possibility of Ar excess and/or loss (see discussion in Janasi et al. 2011, p. 149; Florisbal et al. 2014, p. 148). Nevertheless, it appears that older low-Ti volcanics outcropping mainly in the southeastern part of the Paraná basin were emplaced over a very short interval at 135–134 Ma, and younger high-Ti volcanics in the more northerly and westerly parts of the basin between at least 134–131 Ma (summary in Florisbal et al. 2014). U-Pb ages of 134.7–133.9 Ma for radiating dykes of the Florianópolis subswarm that are chemically similar to the younger volcanics suggest emplacement at the beginning of the second volcanic phase (Florisbal et al. 2014). Ar–Ar ages for high-Ti radiating dykes of the Ponta Grossa subswarm (Renne et al. 1996) fall in the narrow range between 133 and 131 Ma, consistent with emplacement during the second volcanic phase. There are no U-Pb ages for the proposed circumferential dykes. However, in some cases Ar–Ar ages appear to be younger than for the radiating set. For example, Renne et al. (1996) obtained 122 Ma ages for a pair of high-Ti dykes intersecting the Ponta Grossa radiating subswarm at right angles, suggesting that they could have been intruded long after the main phases of volcanism (Florisbal et al. 2014). Much more precise dating is needed to clarify the ages of the proposed circumferential and radiating swarms.

Kochikha dykes of Siberian Traps LIP (250 Ma): A coupled giant circumferential and radiating system (Fig. 5) was proposed by Ernst and Buchan (1998, 2001) on the basis of available mapping of dykes associated with the Siberian Traps LIP. The Kochikha circumferential swarm has a pronounced elliptical shape (maximum and minimum outer diameters of ~600 and 300 km) and shares a common centre with the radiating swarm. The circumferential swarm spans an arc of ~150°. The radiating swarm (comprising the Ebekhaya and Maimecha subswarms and linear feeder zones to volcanic flows of the Noril'sk area) extends far beyond the circumferential system to a distance of 900 km from its focus. The circumferential dykes crosscut Siberian Traps volcanics, whereas the radiating dykes do not, indicating that the circumferential dykes are younger that the radiating set.

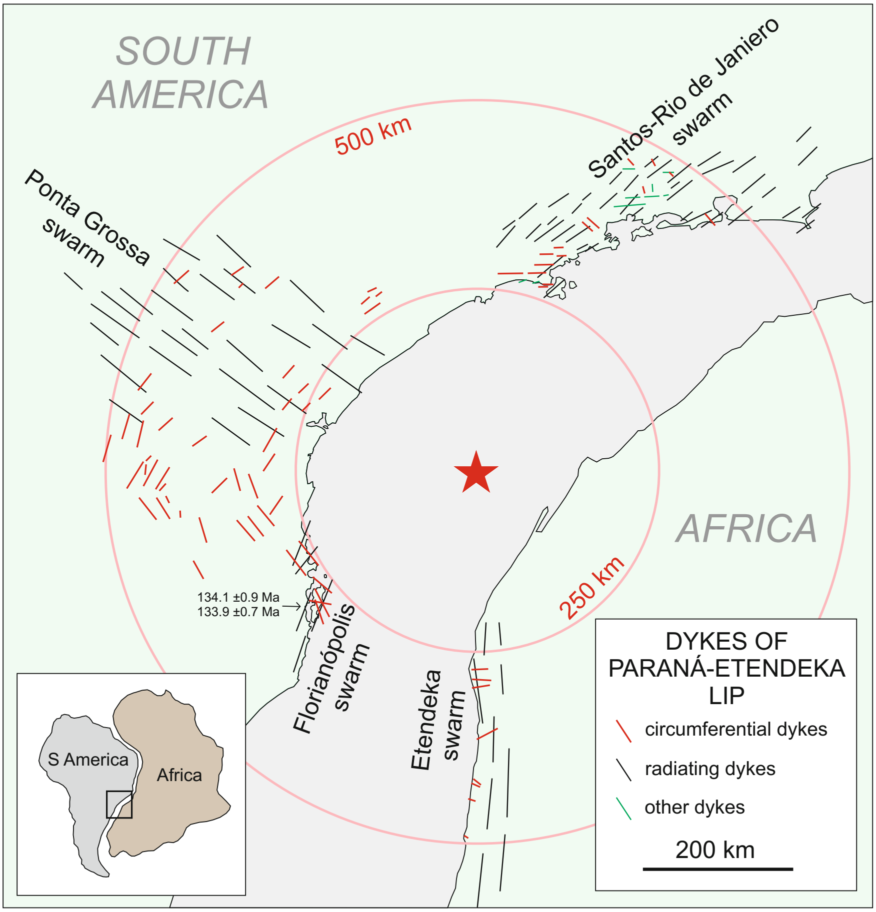

Fig. 4 Circumferential (red) and radiating (black) dykes of the reconstructed ca. 135–120 Ma Paraná-Etendeka LIP of Brazil and Namibia. The radiating swarm is dense in some areas, and has been thinned on the figure for the sake of clarity. Circumferential dykes are from various sources listed in the text. The reconstruction is from Torsvik et al. (2009). Pink circles indicate the approximate outer and inner dimensions of the circumferential swarm. The red star is the centre of the circumferential swarm and the focus of the radiating swarm. U-Pb ages for radiating Florianópolis dykes are shown in black lettering

Blekinge-Dalarna dykes of Rogaland event, Sweden (ca. 978–946 Ma): The Blekinge-Dalarna swarm (Fig. 6; Gorbatschev et al. 1987; Bylund 1992; Söderlund et al. 2005) follows the eastern margin of the high-grade Protogine Zone, which separates the Svecofennian and Sveconorwegian domains of the Baltic Shield in Sweden. It has a length of 700 km, an arc of ~60°, and is truncated to the north by the Caledonian orogeny and overlain to the south by Phanerozoic cover rocks. Ernst and Buchan (1998) proposed that the swarm may represent a giant circumferential

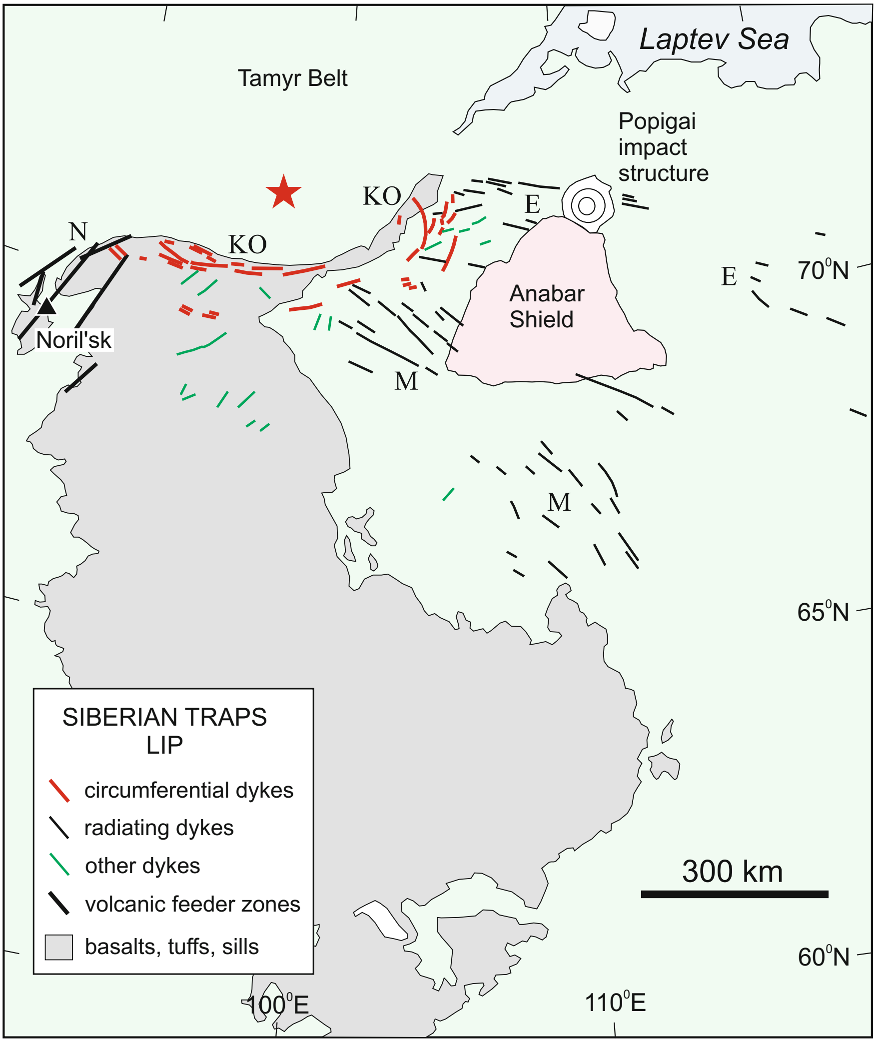

Fig. 5 Circumferential (red) dykes and radiating (black) dykes and volcanic feeder zones of the ca. 250 Ma Siberian Trap LIP (modified after Ernst and Buchan (2001), with additional circumferential dykes from Ryabov et al. (2014, Fig. 2.30)). The red star locates the approximate focus of the radiating swarm and the centre of the circumferential swarm. E = Ebekhaya dykes; KO = Kochikha dykes; M = Maimecha dykes; N = Noril'sk feeder zones to volcanic flows. The circumferential dykes cut the volcanics, whereas the radiating dykes do not

system (outside diameter of 1100 km) about a centre near the prominent 932–929 Ma (Schärer et al. 1996) Rogaland complex. More recently, precise U-Pb dating has confirmed that the dykes along the length of the swarm are of approximately the same age (978–946 Ma; Söderlund et al. 2005). Consistent paleomagnetic directions along

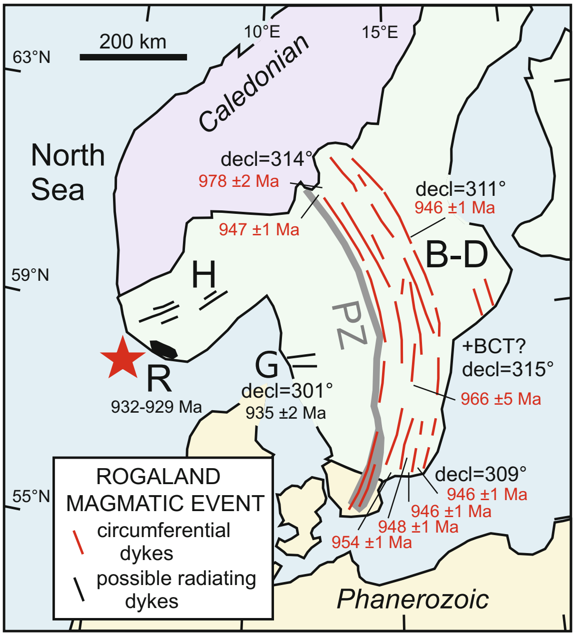

Fig. 6 Circumferential (red) dykes of the ca. 978–946 Ma Blekinge-Dalarna (B-D) swarm of the Rogaland magmatic event, Sweden. The red star locates the centre of the swarm. The slightly younger (ca. 935 Ma) Göteborg (G) dykes (black) could represent part of a radiating swarm. Dykes of the Hunnedalan (H) swarm (black) could also be part of a radiating swarm, but are poorly dated. Paleomagnetic declinations obtained at various locations along the Blekinge-Dalarna swarm (Pisarevsky and Bylund 2006) are labelled 'decl.' The label '+BCT?' locates a probable positive baked contact test indicating the remanences are primary. U-Pb ages for the Blekinge-Dalarna dykes (Söderlund et al. 2005) are in red lettering. U-Pb ages for the Göteborg dykes (Hellström et al. 2004) and the Rogaland complex (Schärer et al. 1996) are in black lettering

the swarm (summarized in Fig. 6, from the compilation in Pisarevsky and Bylund 2006) indicate that its arcuate geometry is primary. Dykes of the small Göteborg (Tuve) swarm (Fig. 6) have been dated at 935 ± 2 Ma (U-Pb; Hellström et al. 2004), somewhat younger than the Blekinge-Dalarna swarm, and could represent part of a radiating system in the interior of the circumferential swarm.

Keewenawan dykes of Mid-Continent Rift, central North America (ca. 1110–1085 Ma): Ernst and Buchan (1998) described dykes of the ca. 1110–1085 Ma Keweenawan LIP that ring the northern shore of Lake Superior (Fig. 7) as a giant circumferential dyke swarm, and suggested that opening of the Mid-Continent Rift may have occurred along the extensional belt defined by the circumferential swarm. The northern portion of the black ellipse shown in Fig. 7 roughly matches the geometry of the rift system in the Lake Superior region, as well as the curvature of the dyke swarms along the northern Lake Superior shore (cf., red ellipse segment), provided that the dyke swarms are shifted ~80 km southward to take account of the opening of the rift. The centre of the black ellipse is close to the Goodman swell (Peterman and Sims 1988) which may locate the centre of an underlying mantle plume (Hutchison et al. 1990; Ernst and Buchan 1997). No radiating swarm has been identified which is coeval with the Keweenawan magmatism, although a few isolated dykes may fit a radiating geometry. However, the somewhat older 1141 ± 2 Ma (U-Pb, Krogh et al. 1987) Abitibi diabase dykes (Fig. 7) and ca. 1144 Ma lamprophyre dykes (U-Pb, Ar–Ar; Queen et al. 1996) could represent part of a radiating swarm that was a precursor to the Keweenawan event (see discussion in Queen et al. 1996; Heaman et al. 2007), given that they focus near the Goodman swell. An imprecise U-Pb age of 1140 ± 20 Ma has been reported for a Pigeon River (Thunder Bay) dyke (Heaman et al. 2007), suggesting that there could be a component of the circumferential swarm that was emplaced prior to the Keweenawan event. However, some of the circumferential dyke swarms shown in Fig. 7 intrude Keweenawan rocks, and therefore cannot be pre-Keweenawan in age. In particular, many Pigeon River dykes intrude early Keweenawan Logan sills and many Copper Island dykes crosscut early Keweenawan Olser volcanics. The overall time span for emplacement of the circumferential dykes is not known and will require more U-Pb dating.

Lake Victoria dykes of Kunene-Kibaran LIP, east Africa (ca. 1370 Ma): The Lake Victoria giant circumferential swarm (Mäkitie et al. 2014; Ruotoistenmäki 2014; Ernst et al. 2014), which is associated with the Kunene-Kibaran LIP (Mäkitie et al. 2014; Ernst 2014), has a circular geometry over an arc of 160° and an outer diameter of ~650 km (Fig. 8). It is a prominent feature on aeromagnetic maps of the region. The swarm is only imprecisely dated at 1374 ± 42 Ma and 1368 ± 41 Ma (Sm–Nd; Mäkitie et al. 2014). There is no associated giant radiating dyke swarm. However, numerous roughly coeval sills, layered intrusions and granitoids are located within the circumferential swarm. It is uncertain whether the "dykes" are vertical. Geophysical modelling suggests inward-dipping cone sheets (Ruotoistenmäki 2014), whereas field descriptions indicate the presence of some subvertical dykes (Mäkitie et al. 2014).

2.2 Possible Giant Circumferential Dyke Swarms and Swarm Segments

There are a number of cases in which a set of dykes appears to form a circumferential pattern, but the overall distribution of dykes in the region is rather complicated, or the possibility of secondary deformation has not been ruled out. In other cases, dating of the dykes of an apparent circumferential system is currently inadequate and further study is needed to confirm that the dykes are all related to the same magmatic event. In addition, there are examples in which a small dyke swarm without a clear arcuate geometry is perpendicular to coeval dykes of a giant radiating swarm, suggesting that the small swarm could represent a segment of a giant circumferential swarm with its

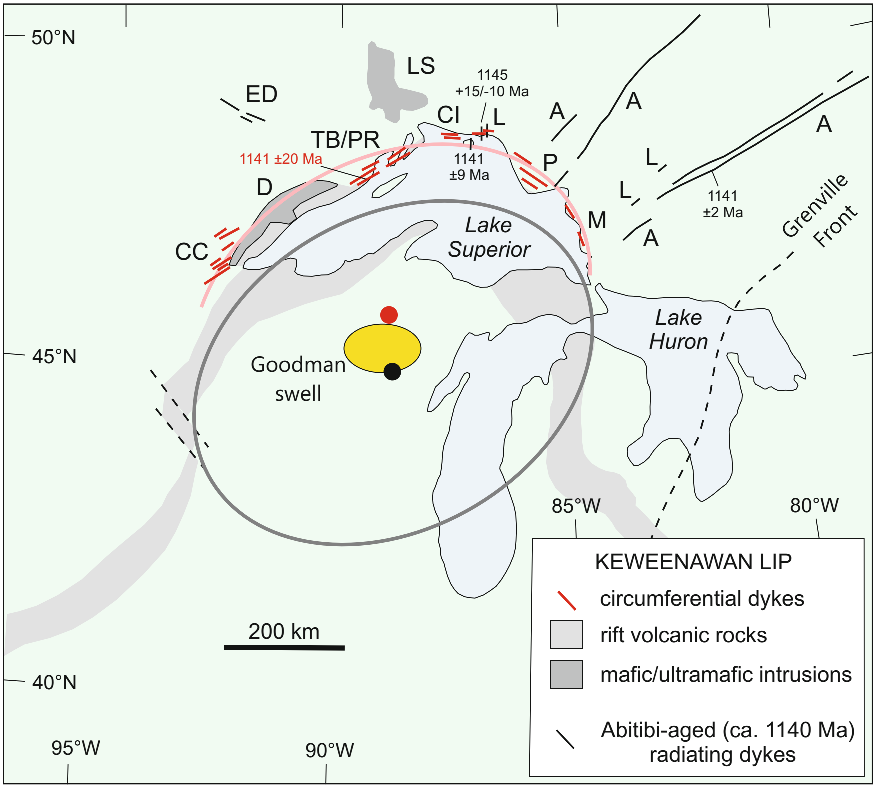

Fig. 7 Circumferential (red) and radiating dykes (black) of the ca. 1110–1085 Ma Keweenawan LIP and ca. 1140 Ma Abitibi magmatic event associated with the Mid-Continent Rift of North America. Rift-parallel dyke swarms: CC = Carleton County, TB/PR = Thunder Bay (Pigeon River), CI = Copper Island, P = Pukaskwa, M = Mamainse Point. Other mafic/ultramafic intrusions: D = Duluth anorthosite complex, LS = Logan (Nipigon) sills. Radiating dykes: A = Abitibi dykes, ED = Eye Dashwa dykes. L = lamprophyre dykes. Dykes are modified from Buchan and Ernst (2004). The Goodman swell (Peterman and Sims 1988) may locate the centre of a Keweenawan mantle plume as described in the text. The northern portion of the black ellipse (centred at the black dot) roughly matches the geometry of the rift system in the Lake Superior region. If shifted north ~80 km (as the pink arc centred at the red dot) to reflect opening of the rift, it roughly matches the curvature of the dyke swarms along the northern Lake Superior shore. Linear Keweenawan Baraga and Mellen-Gogebic dyke swarms (e.g., Buchan and Ernst 2004) that occur south of Lake Superior are not shown. Their trends are not consistent with either the radiating or circumferential systems. U-Pb ages for radiating Abitibi (Krogh et al. 1987) and lamprophyre (Queen et al. 1996) dykes are shown in black lettering. A U-Pb age for a Pigeon River circumferential dyke (Heaman et al. 2007) is shown in red. This age suggests emplacement well before the Keweenawan event. However, many dykes of the circumferential system (including some Pigeon River dykes) are observed to cut Keweenawan sills and volcanics and hence cannot be pre-Keweenawan in age

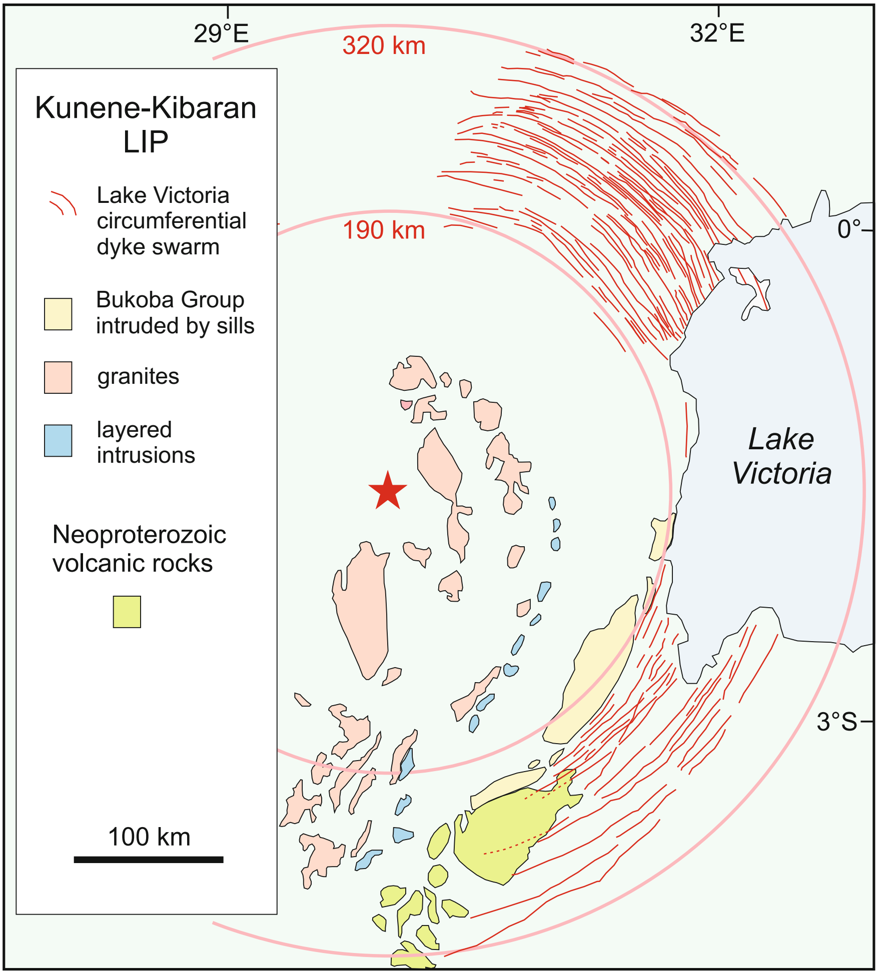

Fig. 8 Ca. 1370 Ma giant circumferential Lake Victoria dyke swarm of the Kunene-Kibaran LIP of eastern Africa, traced mainly from aeromagnetic data. Dashed pink circles indicate the approximate outer and inner dimensions of the swarm. The red star locates the centre of the swarm. The figure is modified after Mäkitie et al. (2014), with the Bukoba Group after Tack et al. (2010)

centre at the focus of the radiating swarm. Several examples of possible swarms are described briefly below.

Dykes of British-Irish portion of North Atlantic LIP (62–54 Ma): SSE- to SE-trending dykes associated with the North Atlantic LIP (or North Atlantic Igneous Province, NAIP) form a dense swarm across Britain and Ireland (Fig. 9; e.g., Speight et al. 1982; Cooper et al. 2012) and may represent part of a giant radiating swarm focused above the Iceland mantle plume. See a reconstruction of the North Atlantic LIP in the inset to Fig. 9. Maclennan and Jones (2006) proposed a model of an ellipse-shaped transient uplift (Fig. 9 inset) associated with the arrival of the plume based on observations in sedimentary basins bordering the North Atlantic Ocean. In addition to the dominant SSE-trending dyke swarm of Britain and Ireland, dykes are locally associated with a number of central igneous complexes. These dykes typically occur within a few tens of km or less of the complexes and can be parallel to the SSE swarm, perpendicular to this swarm or form a fan about the complexes (Speight et al. 1982). In addition, small ring dyke or cone sheet swarms occur within or around the edge of the complexes (Emeleus 1982). Finally, dyke swarms at a high angle to the dominant SSE swarm, but not close to central complexes, occur in Ireland, both within the Republic of Ireland and Northern Ireland. They include the ENE Mayo (or West Connacht) swarm (Mohr 1982, 1988; Preston 2001), similarly trending dykes in the Malin Head region (Geological Survey of Northern Ireland 1977) and Belfast region (Walker 1959; Geological Survey of Northern Ireland 1971), as well as the E-trending Inischrone (or North Connacht) swarm (Mohr 1987, 1988; Preston 2001). It has been suggested that the Mayo dyke swarm may emanate from the offshore Brendan complex (e.g., Mohr 1982) shown on Fig. 9. However, this swarm extends nearly 200 km from the centre of the Brendan complex, many times farther that the dykes associated with other central complexes. We suggest that the Mayo swarm and the similarly trending dykes of the Malin Head and Belfast regions may belong to a giant circumferential dyke swarm that parallels the outer edge of the elliptical uplift described by Maclennan and Jones (2006), and that is related to the outer edge of the flattened plume head. The Inischrone swarm, which comprises a dense system of very narrow dykes (usually <2 m) (Mohr 1987), may have a more local source. It is not clear if the proposed circumferential swarm extends into Scotland, but we suggest that two long ENE-trending dyke segments (labelled SUF in Fig. 9) adjacent to the Southern Upland Fault, that are at right angles to the dominant SSE dyke swarm, and have been interpreted as right-angle bends in SSE-trending dykes (MacGregor 1949; MacDonald et al. 2014), may actually be part of the circumferential swarm. The Mayo and Inischrone swarms of western Ireland are interpreted to belong to the North Atlantic LIP event based on K-Ar and Ar–Ar dating (e.g., Thompson 1985; Mitchell and Mohr 1986). However, the relative ages of the proposed circumferential and radiating swarms is not clear and will require more detailed studies.

Dykes of Madagascar LIP, Madagascar and southern India (ca. 92–88 Ma): The 92–88 Ma Madagascar LIP in Madagascar is characterized by widespread flood basalts and dykes associated with the breakup of Madagascar and India (e.g., Storey et al. 1995; Melluso et al. 2009; Cucciniello et al. 2013, 2015). Ernst and Buchan (1997) proposed that the dominant dyke sets form a giant radiating swarm focused on the Marion plume centre off the southeast corner of the island (Fig. 10). Subsidiary dyke sets intersect the dominant system roughly at right angles (Fig. 10). We suggest that they may represent components of a giant circumferential swarm with outer diameter of ~2400 km. In addition, coeval dykes have been identified in southern India (Fig. 10), paralleling the west coast (Radhakrishna et al. 1990; Radhakrishna and Joseph 2012), and inland perpendicular to the coast (Kumar et al. 2001). How the southern India dykes relate to the pattern of dykes in Madagascar is uncertain because the exact reconstruction of Madagascar and India is controversial. Nevertheless, using