Early syn-rift igneous dike patterns, northern Kenya Rift (Turkana, Kenya): Implications for local and regional stresses, tectonics, and magma-structure interactions

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ABSTRACT

Four areas (Loriu, Lojamei, Muranachok-Murungangapo, Kamutile Hills) of well-developed Miocene-age dikes in the northern Kenya Rift (Turkana, Kenya) have been identified from fieldwork and satellite images; in total, >3500 dikes were mapped. Three areas display NNW-SSE—N-S-oriented dike swarms, with straight, radial, and concentric patterns in zones <15 km long, and indicate NNW-SSE to N-S regional maximum horizontal principal stress (S_{Hmax}) directions in the early to middle Miocene. Individual dikes are typically <2 m wide and tens to hundreds of meters long and have accommodated <2% extension. In places (Loriu, Lojamei, Lokhone high), dikes trend at a high angle to the rift trend, suggesting some local influence (e.g., overpressured magma chamber, cracked lid—style dike intrusions over a sill or laccolith, preexisting fabric in basement) on orientation, in addition to the influence from regional stresses. Only a minor influence by basement fabrics is seen on dike orientation. The early- to middle-Miocene dikes and extrusive activity ended a long phase (up to 25 m.y.) of amalgam half-graben development in central Kenya and southern Turkana, which lay on the southern edge of the early (Eocene—Oligocene) plume activity. The Miocene dike sets and extension on major border faults in Turkana contrast with larger, more extensive arrays of dikes in evolved systems in the Main Ethiopian Rift that are critical for accommodating crustal extension. By the Pliocene—Holocene, magmatism and intrusion along dikes had become more important for accommodating extension, and the tectonic characteristics began to resemble those of rift basins elsewhere in the eastern branch of the East African Rift.

INTRODUCTION

The geometries of shallow igneous intrusive systems in rifts are highly varied, and range from those dominated by dikes and pipes, to those where sills (fed by dikes and/or transgressive sills) dominate the shallow systems, particularly in syn-rift sedimentary basins (Galerne et al., 2011; see reviews in Magee et al. [2016] and Galland et al. [2018]). The nature of these highly variable shallow intrusion systems provides information about differences in volcanic plumbing systems (e.g., Bell and Butcher, 2002; Smallwood and Maresh, 2002; Plante et al., 2005; Cartwright and Hansen, 2006; Schofield et al., 2018; Magee et al., 2017), magma-fault interactions (e.g., Rateau et al., 2014; Schofield et al., 2016; Muirhead et al., 2016; Dumont et al., 2017; Morley, 2018), upper crustal stress variations in rifts (Muirhead et al., 2015; Robertson et al., 2015; Wadge et al., 2016), interaction between magmatic activity and petroleum systems (Schutter, 2003; Senger et al., 2017; Spacapan et al., 2018), and the processes controlling extension in rifts (e.g., Swain, 1992; Ebinger and Casey, 2001; Buck, 2004, 2006; Bialas et al., 2010; Karakas and Dufek, 2015; Ebinger et al., 2017). Interactions between syn-rift basins, rift structure, and igneous processes vary greatly between rifts, and first-order differences can largely be explained in terms of passive versus active rifts (see review in van Wyk de Vries and van Wyk de Vries [2018]). There are also important temporal and spatial differences within passive and active rifts. For the East African Rift, which is an active rift, several studies (Muirhead et al., 2015; Robertson et al., 2015; Wadge et al., 2016) have explored interactions between structure and magmatism in the upper crust by investigating stress orientations inferred from cone lineaments and caldera ellipticity (dikes were insufficiently well exposed). Muirhead et al. (2015) suggested that variable lineaments were the result of interplay between the regional stress field, local magma-induced stress fields, and stress rotations caused by interaction between rift segments. Preexisting structures may influence the storage and orientation of deeper magma reservoirs, while shallow magmatism and intra-rift faulting are affected by the local stress regime (Robertson et al., 2015), which can be influenced by the loading effects of large topographic features such as rift flanks and major volcanic ediﬁces (Maccabber et al., 2014; Wadge et al., 2016).

There are few studies in the East African Rift (Fig. 1) that assess the relationships between the large-boundary-fault stage of rifting and dike emplacement in the upper crust in parts of the rift system where igneous activity is less dominant (e.g., Muirhead et al., 2015). The reasons for this paucity of studies partly lie in the difﬁculty of ﬁnding a region of good exposure where a diversity of rift-basin settings can be found coupled with the right erosion levels to reveal dikes; in this respect, the Turkana area (Figs. 1, 2) of northern Kenya is an exception. In Turkana, there are a number of Cenozoic rift basins that were initially filled by base ment-derived alluvial, ﬂuvio-deltaic, and lacustrine deposits, and were then ﬁlled by extrusive igneous deposits and clastics with a strong volcanic source component (Morley et al., 1992, 1999a; Vétel et al.,...
2004; Muia, 2015), while contemporaneous basins further north have been filled predominantly by volcanic and volcaniclastic rocks (Boschetto et al., 1992). In some of the Turkana basins, erosion has exposed well-developed arrays of dikes (Fig. 2). The dikes occur in areas that have only been infrequently visited by geologists, although one of the areas described, in the Lokichar Basin (Fig. 2), has become a production area for hydrocarbons, which has considerably opened up the outcrops around that basin. This paper discusses the occurrences and morphology of well-exposed dike swarms in four areas in Turkana: Muranachok-Muruangapoi, Kamutile Hills, Lojamei (South Lokichar Basin), Loriu (Fig. 2). This is a preliminary study based largely on analysis of satellite images, whereby >3500 dikes have been mapped. To a limited extent, this analysis is supplemented by fieldwork that the author conducted in the area at various times between 1987 and 2013. However, that work was focused on the petroleum system of the area (Morley et al., 1992, 1999a; Wescott et al., 1993, 1999; Talbot et al., 2004; Tiercelin et al., 2004), not the igneous activity, although some basic information about the intrusions was gathered. This information is supplemented by work from other studies in the region, notably Vétel (2005), Vétel et al. (2004), Vétel and Le Gall (2006), Tiercelin et al. (2012a), and Muia (2015). The primary aims behind this study are: (1) to describe the relationships of dike sets to structural location at a time when continental extension by faulting, particularly during the formation of half grabens, in the brittle crust was the primary mode; (2) to use the dike orientations to infer the stress orientations at particular times during the Cenozoic development of the Turkana part of the eastern branch of the East African Rift; (3) to assess whether relationships between dikes, rift structures, and preexisting fabrics can be identified; and (4) to assess differences and similarities between dikes developed during the half-graben phase of development in Turkana and those in Ethiopia, Afar, and southern Kenya to understand whether the dikes are highly active in accommodating crustal extension, or are secondary features to faulting (e.g., Hayward and Ebinger, 1996; Keranen et al., 2004; Keir et al., 2006; Bastow et al., 2010; Vétel et al., 2004).
Ebinger et al., 2010; Belachew et al., 2013; Beutel et al., 2010; Weinstein et al., 2017; Ebinger et al., 2017; Dumont et al., 2017; Rooney et al., 2018).

**GEOLOGICAL BACKGROUND**

Outside of the initial preliminary studies of the area (e.g., Walsh and Dodson, 1969; Hackman et al., 1990), historically, a wide range of geological studies in the Turkana region have arisen largely as a consequence of research into hominids (e.g., Cerling and Brown, 1982; Feibel et al., 1989; Boschetto et al., 1992; McDougall and Brown, 2005; Feibel, 2011; Brown and Jicha, 2016) or hydrocarbon exploration (Morley et al., 1992, 1999a; Dunkelman et al., 1988, 1989; Karson and Curtis, 1994; Talbot et al., 2004; Tiercelin et al., 2004, 2012a, 2012b; Vétel et al., 2004; Le Gall et al., 2005a; Vetel and Le Gall, 2006). The focus of both types of study has been the sedimentary section, although the extensive tracts of volcanic and pyroclastic units are useful for reconstructing the tectonic history of the area, understanding the paleo-geomorphology and sediment provenance, and providing radiometric ages of the basin fill.

Seismic reflection data have demonstrated that there are a number of half-graben rift basins in western Turkana (e.g., Turkana, North Lokichar, Lokichar, and Kerio Basins, Fig. 2; Morley et al., 1992, 1999a; Vetel, 2005; Vetel and Le Gall, 2006), Lake Turkana (Dunkelman et al., 1988, 1989), and the Omo Basin (Alemu, 2017). The age of rifting is diachronous and spans the time period between the Eocene and the present day; there is a general easterly and southerly younging in both rift-basin and volcanic activity (Fig. 3; Morley et al., 1992, 1999a; Vetel, 2005; Vetel and Le Gall, 2006; Boone et al., 2018b). Some basins or stages in basin development are filled primarily by basement-derived coarse clastics and lacustrine shales, while other basins or stages in basins are dominated by lavas and pyroclastic and volcaniclastic deposits (Boschetto et al., 1992; Morley et al., 1999a; Vetel and Le Gall, 2006; Fig. 3). The eastward migration of extensional activity has caused the Turkana region to be the widest part of the East African Rift, forming an ~250-km-wide

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**Figure 2.** Topographic map (digital elevation model, slope-shader image Aster Global Digital Elevation Map) of the Turkana region, Kenya, showing key rift features and the location of the study area. Rift structure is from Morley et al. (1999a), with some modification from satellite image interpretation (this study) and from Vetel et al. (2005) and Vetel and Le Gall (2006). FWU—footwall uplift.
volcanics, Balesa-Koromto Unit, Turkana Volcanics; (Fig. 5; Morley et al., 1999a). The Eocene–Oligocene (Davidson and Rex, 1980; Ebinger, et al., 1993, 2000; (e.g., Keller et al., 1994). This line shows that the Late Miocene volcanism to the Miocene volcanism, and a shift to the southeast from the Eocene–Oligocene (outside of the Afar Triangle and North Tanzania 2006; Corti et al., 2019). The main Pliocene–Holocene volcanic activity is also focused along Lake Turkana (e.g., South, Central, and North Islands) and on the eastern side of the lake (Mount Kulal, Mount Marsabit) (Hackman et al., 1990; Curtis, 1991; Karson and Curtis, 1994).

A north-south seismic wide-angle reflection-refraction profile was acquired on the western side of Lake Turkana as part of the KRISP 90 program (e.g., Keller et al., 1994). This line shows that the crust west of the lake is as thin as 20 km (Keller et al., 1994; Khan et al., 2000). Gravity modeling indicates that this zone of crustal thinning trends north-south and runs along the northern half of Lake Turkana (Fig. 1B). Estimates of upper crustal extension, related to superimposed Cretaceous, Paleogene, and Neogene rifting events, from balanced cross-sections and flexural models are ~35–40 km (Morley et al., 1992; Hendrie et al., 1994).

In southern Ethiopia and northern Turkana, the presence of 45–35 Ma tholeiitic basalts and associated silicic extrusives (Amaro-Gamo Unit, Chibelet volcanics, Balesa-Koromto Unit, Turkana Volcanics; see review in Rooney (2017)) indicates that anomalously hot mantle related to a mantle plume had arrived beneath northeastern Africa by 40–45 Ma (Davidson and Rex, 1980; Ebbing, et al., 1993, 2000; George et al., 1998; George and Rogers, 2002; Pik et al., 2006). In northwestern Turkana, the oldest lavas are of late Eocene age (Fig. 5; e.g., Zanettin et al., 1983; Bellieni et al., 1987; Rooney, 2017). The lavas extend to the eastern side of Lake Turkana in the Kajong area (Fig. 2), where a sample was 40Ar/39Ar dated at 39.2 ± 04 Ma by Furman et al. (2006).

The key evolution in volcanism in Turkana is a shift to the southeast from the Eocene–Oligocene volcanism to the Miocene volcanism, and a shift to the east from the Miocene to the Pliocene–Holocene (Fig. 5; Morley et al., 1999a). The Eocene–Oligocene volcanism covers a region today that extends from northwestern Turkana, where the crust is relatively thick, to the central area of Lake Turkana, which today is the main zone of thinning. The igneous activity is associated with very shallow partial melting of the mantle (50–65 km; Furman et al., 2006). Extension during Cretaceous-Eocene was likely episodic. Lapur Sandstones have no obvious fault control. b—Based on Figure 5 (and related references). c—Equivalent to the Orange horizon of Morley et al. (1999a); 13—Haileab et al. (2004); 14—Boone et al. (2018b); 15—Wescott et al. (1993); 16—Muia (2015); 17—Ducrocq et al. (2011); 18—Boone et al. (2019); 19—Chapman et al. (1978); 20—Hautot et al. (2000); 21—Morley et al. (1992); 22— Bosworth and Maurin (1993). Notes: a—Timing of extension is uncertain; basin underlies an Eocene–Oligocene volcanic series imaged on seismic data and gravity data (Wescott et al., 1999). Extension during Cretaceous-Eocene was likely episodic. Lapur Sandstones have no obvious fault control. b—Based on Figure 5 (and related references). c—Equivalent to the Orange horizon of Morley et al. (1999a).

Figure 3. Correlation of extensional episodes and stratigraphy in Turkana and central Kenya. Based on Morley et al. (1999a) and Brown and McDougall (2011), modified and/or supported by the following studies: 1—Boone et al. (2018a); 2—Ragon et al. (2018); 3—Brown and Jicha (2016); 4—Wescott et al. (1999); 5—Zanettin et al. (1983); 6—Tiercelin et al. (2012a); 7—O’Connor et al. (2011); 8—Abdelfettah et al. (2016); 9—Ebinger and Ibrahim (1994); 10—Ovusu Agemang et al. (2011); 11—Boschetto et al. (1992); 12—Morley et al. (1999a); 13—Haileab et al. (2004); 14—Boone et al. (2018b); 15—Wescott et al. (1993); 16—Muia (2015); 17— Ducrocq et al. (2010); 18—Boone et al. (2019); 19—Chapman et al. (1978); 20—Hautot et al. (2000); 21—Morley et al. (1992); 22— Bosworth and Maurin (1993). Notes: a—Timing of extension is uncertain; basin underlies an Eocene–Oligocene volcanic series imaged on seismic data and gravity data (Wescott et al., 1999). Extension during Cretaceous-Eocene was likely episodic. Lapur Sandstones have no obvious fault control. b—Based on Figure 5 (and related references). c—Equivalent to the Orange horizon of Morley et al. (1999a).

Study areas: I—Muranachok-Muruangapoi, II—Napadet-Kamutile-Kathigithigiria Hills; III—Loriu; IV—Lojamei. Other abbreviations: Fm—Formation; Ld?—basin fill seen on seismic reflection data, but has not been drilled, probably equivalent stratigraphy to that in Lokichar Basin or the Loriu area.
and probably the onset of a new mantle thermal anomaly, plus the effects of lithospheric stretching, both had an effect on Miocene volcanism. An alternative explanation to plume-related melting for the 16–23 Ma volcanism in Turkana is partial melting related to detachment of a plume-metasomatized “drip” of lithosphere that descended into the asthenosphere (Furman et al., 2016), where the crust is showing increased thickness (Fig. 1B, 4), indicates that partial melting within the mantle is more strongly influenced by mantle temperature anomalies than by lithospheric stretching.

### METHODOLOGY

Dikes and other geological features were interpreted within Global Mapper software (https://www.bluemarblegeo.com/products/global-mapper.php), using the U.S. National Aeronautics and Space Administration (NASA) Aster Global Digital Elevation Map (DEM) V2 data sets (https://asterweb.jpl.nasa.gov/gdem.asp). World Imagery ESRI server of Community maps program, SPOT satellite images, https://www.arcgis.com/home/item.htm?id=10df2279f9684e4a9f6a7f08febac2a9 provides variable-resolution data that typically is 1 m or better, but can be of lower resolution in some areas.

Metho...yed (Fig. 2) dates from 2011 and has a resolution of 0.5 m and an accuracy of 10.2 m. Dikes as small as ~1–2 m in width (and probably smaller) are imaged, and can be mapped on this data set. Typically dikes that run for hundreds of meters to kilometers in length in Turkana are ~1–10 m wide. The World Imagery data were overlain on the Aster DEM data set, which has a resolution of 1 arc-second (~30 m in Kenya). Hence the DEM data are good for providing general topographic information but lack the resolution to aid in interpretation of dikes. Interpretation of features was cross-checked with that of previous publications (in particular: Morley et al., 1999a; Vetel, 2005; Tiercelin et al., 2012a; Muia, 2015) and unpublished material from previous expeditions I was involved with. Turkana is arid to semiarid and has little tree cover. Young alluvial, fluvial, lacustrine, and aeolian deposits commonly mask the bedrock. But there are also extensive tracts where bedrock is exposed almost 100%. Geological maps of the areas used in this study are from Morley et al. (1999a) and Vetel (2005). The Loriu area geology was remapped based on previous unpublished field notes of the author and satellite images.

Dikes have a variety of characteristics on satellite data. Most typically they are composed of dark gray to black basalt, and so form thin, linear,
erosionally resistant features that are darker than the adjacent regions. Dikes are commonly so thin (<1 m) that they are not imaged clearly. The wider dikes (~5–10 m), particularly those in the Lojamei area, display internal features; in particular, in some cases chilled margins tend to be more resistant to weathering, and so stand higher than the center of the dike (Fig. 6). In other examples, an apparently wide dike is actually the product of two or three separate intrusive events. The effects of chilled margins or multiple intrusion events can be confusing in some areas on satellite images, because such dikes can resemble a straight dirt road. This is particularly an issue in the Lojamei area, where a grid of linear, bulldozed, seismic reflection lines are present. Another area where the appearance of dikes is atypical is the Napadet-Kamutile-Kathigithigira (NKK) Hills (Fig. 7). The presence of the white material seen in Figure 7 is related primarily to wind-blown sediment and to sediment (commonly diatomaceous lacustrine deposits and pyroclastic deposits) interbedded within the volcanic sequence. The dikes form subtle topographic ridges that trap the sediment. It is a problem that some straight bedding trends, fractures, and faults are also associated with linear tracks of white sediment, hence the presence of dikes had to be verified when mapping. Conversely, this probably meant that some white tracks associated with sub-satellite-resolution dikes remained unmapped, and there is probably overinterpretation of dikes as well.

In some areas, particularly where dikes are wide (>5 m), the relative timing of different dike sets can be established. This is particularly useful in the Lojamei area where a few dikes of different orientations have been dated (Morley et al., 1999a; Tiercelin et al., 2004, see Lojamei Dikes section), and this information is complemented by the relative timing of the dikes of different orientations from their cross-cutting relationships seen in the field and from satellite data (Fig. 8). In outcrop, the cross-cutting relationships of dikes are readily observed, but commonly such relationships are not clearly imaged on satellite data, particularly for narrow dikes. Other effects commonly accompany the cross-cutting relationships and so aid in identification of relative timing. These effects are: (1) a small offset in the trend of the older dike (Fig. 8C); and (2) a local change in direction (jog) where the younger dike runs parallel to the older dike for a short distance before resuming its original orientation (Figs. 8A, 8D). Rarely, instead of cross-cutting an older dike, a younger dike may simply be deflected into the orientation of the older dike (Figs. 8B, 8E). A summary of the potential problems of mapping dike traces, widths, and timing in the study area is provided in Table 1. A summary of the published dating of dikes in the study areas in western Turkana is provided in Table 2. Shapefiles (ESRI) of the mapped dike patterns, faults, and other features for this study are available in the Supplemental Files.'

Dikes were initially mapped in Global Mapper without sorting into different types. Subsequently,
the dikes identified in the NKK Hills and Loriu were sorted into groups simply on basic patterns: which dikes looked compatible with a radial dike pattern, or which ones were compatible with ring dike trends. In the Lojamei area, such patterns were not apparent, and whether the different dike trends tended to have consistent relative timing (Fig. 8) was considered instead.

Rose diagrams of linear feature orientations represent the frequency of occurrence of a particular azimuthal trend (commonly divided into 10° or 20° increments). Dike orientations are given as the average orientation for a particular unit length, e.g., 100 m. Hence, all dikes up to 100 m in length would be represented by one orientation each, while a 5-km-long dike counts as 50 orientations. This has the advantage of giving a more accurate weighting when dike lengths are highly variable, and reduces the problems of representing dikes that exhibit variable azimuths.

**DIKE PATTERNS AND TIMING WEST OF LAKE TURKANA**

**Loriu Area**

**Introduction**

The coarse arkosic clastics of the Loriu area (formerly Lariu) are known as the Loriu Sandstone (Muia, 2015). The sandstones are of uncertain age and directly overlie Precambrian gneisses, and in turn are unconformably overlain by early Miocene volcanic rocks with interbedded pyroclastic, volcanioclastic, and lacustrine deposits (Wescott et al., 1993; Muia, 2015). The sandstones are present in a 3.4 km long × 2.6 km wide NE-SW–trending zone (Fig. 9). In places, the sandstones onlap the gneisses; elsewhere, they are in normal fault contact (Fig. 9). The fault geometry changes in a NE-SW direction and gives rise to two main transfer zones, one with a colinear geometry, the other with a relay ramp (Fig. 9). The Precambrian gneisses and Loriu Sandstone were deformed by a phase of normal faulting that occurred prior to extrusion of the volcanic rocks. Subsequently, renewed normal faulting...
during the Miocene–Pliocene tilted the volcanic series. The dips within the Loriu Sandstone are commonly higher and more variable (>30° dip) than would typically be expected for simple normal faulting, suggesting that volcanic intrusions, and possibly inversion, have also deformed the area (Morley et al., 1999a; Le Gall et al., 2005a).

Outcrops of the Loriu Sandstone, volcanic rocks, and to a lesser degree the Precambrian gneisses are extensively intruded by dikes (Figs. 9, 10, 11); possibly thick underlying sills or laccoliths have caused broad monoclinal folding (with bedding dips ~35°–40°NE) along the southwestern margin of the Loriu Sandstone (Fig. 11). Wescott et al. (1993) used whole-rock K-Ar dating to obtain an age of 15.7 ± 0.7 Ma for a basalt sample from the base of the volcanic sequence, and an age of 14.7 ± 0.17 Ma for a dike intruding the sediments (Table 2; see Fig. 9 for locations). The igneous outcrops overly Precambrian gneisses and Loriu Sandstone, and include lavas interbedded with pyroclastic and volcaniclastic deposits and lake beds. Intrusions include basaltic dikes with augite phenocrysts, and agglomerates in vent complexes. Muia (2015) sampled a N110°-trending vertical basalt dike intruding the Loriu Sandstone (Fig. 9). 40Ar-39Ar dating of the dike did not result in definition of a plateau age; a pseudo–plateau age for increments between 10% and 65% of Ar release suggests an age of ca. 18.5 Ma (Muia, 2015; Table 2).

**Intrusions in the Loriu Area**

Dike trends in the Loriu area are separated into two types, comprising radial and non-radial patterns (blue and red dikes, respectively, in Fig. 10). The radial dikes are centered around an eroded volcanic complex (area A in Fig. 10). The longest intrusions are ~2.1 km long, and dikes are commonly in the range of hundreds of meters to 1 km long. On the eastern side of the radial dikes is area B, which comprises a high density of predominantly NW–SE–trending intrusions. The NW–SE–trending dikes reach maximum lengths of ~700 m, and more typically dikes are tens of meters to a few hundred meters long. The presence of other trends gives

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**Figure 8. Satellite images of dikes from the Lojamei area showing criteria for determining the relative timing of dikes. Coordinates of white square are given as locations for the images.**

- **A**: Youngest dike jogs along the trace of the intermediate-age dike for a short distance and cross-cuts the oldest dike.
- **B**: Younger dike deflects into the trace of the older dike.
- **C**: Cross-cutting relationship with small visible offset of older dike.
- **D**: Short deflection of cross-cutting younger dike along older dike trace.
- **E**: Dikes 2 and 3 deflected into the trend of older Dike 1.
- **F**: Suggested scheme for the ages of dikes (color coded to match those shown in A–D) based on limited radiometric dating (Morley et al., 1999a; Tiercelin et al., 2004) and the types of relationships shown in A–D. LOJ are sample numbers in Tiercelin et al. (2004); see Table 2.
TABLE 1. POTENTIAL PITFALLS FOR INTERPRETATION OF DIKES FROM SATELLITE DATA

| Dike feature | Description | Comment |
|--------------|-------------|---------|
| Dike trace   | White sediment that may mask dike, highlight dike, or represent a linear feature unrelated to a dike. Introduces an element of over- and underinterpretation of dike features in the Napadet-Kamulpile-Kathigithigiria Hills. Interruption of dike trace by deposition of recent deposits or younger volcanics results in underestimation of dike trace length. Dike resembles other linear features (e.g., bulldozed dirt tracks), particularly a problem in the Lojamei area. Dike features in Precambrian basement may be much older than the Cenozoic. Dikes that eroded with a consistent dark apron of material strongly resemble those that cut through the Cenozoic section and are very likely to be Cenozoic in age. Linear features that lack this apron are harder to distinguish and may be older dikes that weather in a similar way to gneissic host rock. Sometimes the same trend of dikes can be seen in adjacent Cenozoic rocks, which increases the likelihood that basement-involved dikes of similar orientation are also of Cenozoic age. |
| Dike width   | Satellite resolution issues. In part mitigated by outcrop field observations. Multiple parallel intrusions mistaken for a single intrusion. |
| Dike timing  | Dike segmentation and different depths of exposure due to the presence of a slope, which may create the false perception of cross-cutting relationships. Satellite resolution insufficient to determine timing relationships for most dikes. Only the widest dikes (\(<5\) m) may exhibit observable relationships. The most reliable relative timing is established for wide dikes in a flat rock pavement (this is the case for parts of the Lojamei area). |

TABLE 2. SUMMARY OF RADIOMETRIC AGES OF IGNEOUS INTRUSIONS AND RELATED LAVA FLOWS IN TURKANA, KENYA

| Location | Composition, sample number† | Comments | Age and method | Reference |
|----------|-----------------------------|----------|----------------|-----------|
| Lapur Range | 04°15'01"N, 35°48'23"E | Te, KER 65/05, LOK A5 | Dike, 10 m wide, N60° strike | 27.40 ± 0.66 Ma, 40Ar-39Ar | Tiercelin et al. (2012a) |
| | 04°10'02"N, 35°47'32"E | R, NATH 08/04, 09/04 | Sill and dikes; deep weathering affects dating | 28.73 ± 0.64 Ma, 40Ar-39Ar | Tiercelin et al. (2012a) |
| Lojamei | 02°12'06.42"N, 35°57'36.63"E | DL, LOJ 20 | Dike, 10 m wide, N170° strike | 12.09 ± 1.5 Ma, K-Ar whole rock | Tiercelin et al. (2004) |
| | 02°11'30.02"N, 35°57'18.16"E | AB, LOJ 98-25 | Dike, 5 m wide, N50° strike | 15.70 ± 0.8 Ma, K-Ar whole rock | Tiercelin et al. (2004) |
| | 02°09'34.65"N, 35°58'34.32"E | AB, LOJ 01 | Dike, 2 m wide, N140° strike | 16.5 ± 0.4 Ma, K-Ar whole rock | Tiercelin et al. (2004) |
| | 02°13'42.58"N, 35°59'05.66"E | B | Dike, N025° strike | 15.9 ± 1.2 Ma, K-Ar whole rock | Morley et al. (1992) |
| | 02°12'20.22"N, 35°57'13.24"E | B | Dike, N050° strike; location E, Figure 13 | 11.9 ± 1.9 Ma, K-Ar whole rock | Morley et al. (1992) |
| Muranachok-Murungapoi | 03°42'58"N, 35°20'12"E | R, 87-3182 | Lava flow | 36.0 ± 0.4 Ma, K-Ar anorthoclase | McDougall and Brown (2009) |
| | 03°19'51"N, 35°35'27"E | B, 87-3155 | Lava flow | 16.3 ± 0.2 Ma, K-Ar whole rock | McDougall and Brown (2009) |
| | 03°16'57"N, 35°27'14"E | B, 87-3191 | Lava flow | 16.5 ± 0.2 Ma, K-Ar whole rock | McDougall and Brown (2009) |
| | 03°33'14"N, 35°21'12"E | B | Lava over Muranachok Grits | 18.5 ± 0.7 Ma, K-Ar whole rock | Zanettin et al. (1983) |
| | 03°13'20"N, 35°29'15"E | B | Lava over Muranachok Grits | 25.5 ± 1.2 Ma, K-Ar whole rock | Zanettin et al. (1983) |
| NKK Hills | 02°56'18"N, 35°51'14"E | B, 92-415 | Lava flow | 12.8 ± 0.01 Ma, K-Ar whole rock | McDougall and Brown (2009) |
| | 02°29'01"N, 35°56'27"E | B, 87-1 | Lava flow | 13.9 ± 0.02 Ma, K-Ar whole rock | McDougall and Brown (2009) |
| | 02°29'01"N, 35°56'27"E | B87-3114 | Lava flow | 15.0 ± 0.02 Ma, K-Ar whole rock | McDougall and Brown (2009) |
| | 02°56'59"N, 35°53'12"E | B | Lava flow | 14.9 ± 1.5 Ma, K-Ar whole rock | Morley et al. (1992) |
| | 02°36'47"N, 35°01'27"E | B | Lava flow | 13.2 ± 1.5 Ma, K-Ar whole rock | Morley et al. (1992) |
| Lorii | 02°43'46"N, 36°25'13"E | B | Base of lava flow overlying Lorii Sandstone dike | 15.70 ± 0.7 Ma, K-Ar whole rock | Wescott et al. (1993) |
| | 02°42'26"N, 36°25'29"E | B | Lava flow | 14.70 ± 0.17 Ma, K-Ar whole rock | Wescott et al. (1993) |
| | 02°42'50"N, 36°25'47"E | B | Dike, 1 m wide, 500 m long, N135° strike | Estimate 18.5 Ma, 40Ar-39Ar pseudo-plateau age only | Muia (2015) |

Notes: NKK—Napadet-Kamulpile-Kathigithigiria; AB—alkaline basalt; B—basalt; DL—differentiated lava; R—rhyolite; Te—tephrite. *Locations estimated from position given on map in publication. †Some sample numbers are not present here or in the paper.
rise to a network of dikes that makes for impressive viewing from the air (Fig. 12). Both the orientation and spacing of the intrusions in area B are very different from those of the adjacent radial dike swarm. The third trend of dikes in the area lies northeast of area B and comprises a NE-SW–trending dike set (area C, Fig. 10) that lies approximately parallel to the trend of Precambrian basement foliations. Typical dike lengths are between 50 m and 300 m.

**South Lokichar Basin–Lojamei Area**

The Lokichar Basin is the largest and most accessible sedimentary basin in Turkana, and forms a classic half graben, with the Kerio basement high marking the flexural margin to the east, and the basin thickening westward into the east-dipping Lokichar fault (Morley et al., 1999a; Tiercelin et al., 2004; Fig. 3). Detailed descriptions of the basin have been given by Morley et al. (1992, 1999a), Tiercelin et al. (2004), and Talbot et al. (2004). More recently, hydrocarbons were discovered in the basin by Tullow Oil, which has made it a significant center for exploration. The older section is exposed in numerous low-relief outcrops around the flexural margin of the basin marked by the Lokhone footwall uplift area (Fig. 2). With variable degrees of intensity, these outcrops are intruded by early–middle Miocene basic and intermediate dikes (Morley et al., 1999a, Tiercelin et al., 2004). The intrusions in the southern part of the basin form a particularly dense network and are discussed in the following section.

**Lojamei Dikes**

The dikes are exposed in the lowest volcanic layers and the Oligo-Miocene sediments (predominantly Lokhone Sandstone Formation) that underlie the middle Miocene Auwerwer Basalts and Auwerwer Sandstone Formation in the Lokichar Basin. In the basin center, the volcanic section is ~1–1.5 km thick (Morley et al., 1999a). The uplifted region that exposes the dikes is on the flexural margin of the basin, and in this direction the basin fill thickness rapidly decreases, hence the likely maximum depth of emplacement of the dikes seen at the surface today is <1 km.

The Lojamei area (Figs. 2, 13) is intensively intruded by dikes typically 1–10 m wide. Morley et al. (1999a) and Tiercelin et al. (2004) reported on dikes from the area that were dated using 40K-40Ar whole-rock fractions; the ages range between 16.5 and 12 Ma (Table 2) for dikes with a variety of orientations. The 16.5–15 Ma basalts coincide with a major phase of volcanic activity that affected the probably of late Eocene age (Boone et al., 2019) and comprises basement-derived arkosic fluvial grits and lacustrine shales (Loperot Group; Morley et al., 1999a; Fig. 3). In the late early Miocene to middle Miocene section, volcanic flows and volcaniclastic deposits (Auwerwer Basalts, Auwerwer Sandstone Formation) become important features of the basin fill (Morley et al., 1999a; Tiercelin et al., 2004; Fig. 3). Detailed descriptions of the basin have been given by Morley et al. (1992, 1999a), Tiercelin et al. (2004), and Talbot et al. (2004).
The younger-age dikes coincide with the Auwerwer Basalts (12.5–10.7 Ma) in the Lokichar Basin (Morley et al., 1999a). There is a considerable variety to the dikes in hand specimen: while many are simply dark gray to black, fine-grained basalts, other dikes are porphyritic (commonly augite phenocrysts), contain amygdales filled by white zeolites, or are intermediate in composition and rich in mica. Some mica-rich dikes show a cleavage developed where mica is concentrated and aligned along the chilled margins (e.g., Fig. 13, location A).

**Dike Trends**

The relative timing relationships of some dikes identified from satellite images (Fig. 8) can be matched with the radiometric ages to suggest some preferred trends for dikes of different age: pre–16.5 Ma, N070°–N090° dikes; ca. 16.5 Ma, N130°–N150° dikes; ca. 15–16 Ma, N25°–N60° dikes; ca. 12.9–11.9 Ma, N180°–N160° dikes; and post–11.9 Ma, ~N005°–N020° dikes (but also one N050°-trending dike dated to this age). The N130°–N150° trend is the strongest in the area and gives rise to a number of long dikes (e.g., Fig. 14, dike 1). Small volcanic cones (e.g., Fig. 14, location X) tend to lie on dikes of this trend, or form NNW-SSE alignments of cones. While some relationship between timing and orientation can be defined, it is unlikely that all dikes of a particular age follow a single trend. For example, at small volcanic centers, dikes exhibit a radial geometry (Fig. 14, location Y). The radial geometry could just represent intersection of dikes of different age and orientation, but it is also common for dikes to form simultaneously with a radial geometry at volcanic centers (see review in Tibaldi [2015]). An indication that dikes striking N70°–N120° reflect a particular time period of intrusions comes from the Lokhone area to the north (Fig. 15). This area, which lies in the central part of the Lokichar Basin, displays intrusions in Precambrian gneisses, the Lokhone Sandstone (Oligocene–early Miocene), and the Lokhone Shale (early Miocene). Two dike trends are present, approximately east-west and ~NNW-SSE. For these dikes, there is no indication that they are part of a radial dike swarm, and in a number of places around the margins of the Lokichar Basin, the approximately east-west dike orientations are found. These dikes feed a number of sills intruded into the shales. More radiometric dating, geochemistry, and detailed fieldwork are required to determine how the different pulses of dike intrusion have developed and interacted.
Interpretation

The dikes in the South Lokichar Basin cover the full range of possible orientations from east-west through to north-south, with the attendant implication that the local principal stress directions have rotated spatially and/or with time. The maximum dike lengths are on the order of kilometers: 3.6 km (ENE-WSW trend), 2.7 km (north-south trend), 4.4 km (NNW-SSE trend), 5.4 km (NNE-SSW trend), and 2.0 km (east-west) trend. The period from ca. 17 Ma to 10 Ma coincides with extension in the Lokichar Basin. The main faults in the basin trend north-south to NNW-SSE, with some local NW-SE and NE-SW trends (Morley et al., 1999a). The basin appears to have behaved as a simple extensional half graben (Morley et al., 1999a; Vetel, 2005).

Faults in outcrop exhibit more variety of orientation than those mapped from seismic data (Figs. 2, 13), which may reflect a resolution issue, where smaller-displacement faults exhibit more variety of orientations than the faults apparent on seismic reflection data. This may in turn indicate that some low-displacement faults observed in outcrop responded to local strains and volume changes caused by igneous intrusion emplacement and deflation, rather than the regional stresses affecting the larger-displacement faults. Eight examples of normal faults intruded by dikes were observed during fieldwork (in 1988); they exhibit strikes between N160° and N030° and dips between 55° and 70°, dominantly to the west (Figs. 13, 14). However, the majority of the dikes in the Lojamei area are subvertical, very linear features independent of fault control. Bedding dips are also generally low (<15°; Fig. 13) and so do not exert a control on dike orientation.

The structural position of the Lojamei area is near the flexural margin of the Lokichar Basin. The region lies south of the plunging nose of the Lokhone basement outcrop. To the east, the Precambrian gneiss exposures are limited by the boundary fault of the Kerio Basin. But passing to the south, this NNE-SSW–trending fault abruptly turns to the southeast and dies out (Morley et al., 1999a). However, some splay faults from the fault trend more north-south and reach the northern part of the Lojamei area (Fig. 13) and die out, with some NNW-SSE trending dikes continuing the trend of the fault zone to the south.

The Lojamei area was potentially affected by complex stress patterns during the syn-rift stage, related to stress deflections around the major splay faults. Stress rotations related to fault morphology have been observed in other rift systems; e.g., Tingay et al., 2010). The absence of clear regional stress control on dike orientations may reflect the development of a shallow magma chamber or chambers, or pipes that dominated the local stress conditions, plus stress rotations related to structure.

Napadet-Kamutile-Kathigithigiria (NKK) Hills

The western side of the Napadet Hills corresponds with the flexural margin of the late Miocene–Pliocene North Lokichar Basin, and field observations indicate that the volcanic layers dip...
westward ~8°–10° as a result of rotation in the hanging wall of the Lokichar fault to the west. The eastern margin of the hill is the footwall of two east-dipping boundary faults, the Turkana fault and the Lothagam-Lokhone fault zone (Fig. 16). A few dikes are visible on satellite images on the eastern margin of the Napadet Hills. In outcrop where a large gorge along the Lokichar lugga (lugga is seasonal watercourse) is present (Fig. 16, location Y), extensive deposits related to volcanic centers are exposed in cliffs. Dip amount and direction in the volcanic strata are highly variable, ranging from subhorizontal to locally >70°. While there is structural tilting of the volcanic series related to normal faulting, the high dip values are related to deposition and slumping on unstable, steep volcanic slopes. Slumped units comprising mud flows and volcanioclastics with volcanic blocks and soft-sediment folds are mixed with agglomerates, lavas (basalt, trachyte, phonolite), lava bombs, agglomerates, tuffs, lapilli tuffs, and intrusions. The strike directions of subvertical intrusions in outcrop are predominantly north-south and NE-SW, with a few oriented east-west. While some dikes are composed of basalts and trachytes, a number of dikes are filled by pyroclastic rocks. One 2-m-wide pyroclastic dike that strikes N045° and dips 64°N was observed to be intruded along a normal fault. On satellite images, these pyroclastic dikes form distinctive narrow (<5 m), linear, light gray to white features against the dark-colored volcanic rocks. They are spaced tens to hundreds of meters apart. Intrusions in the Napadet Hills are generally more widely spaced and absent of the cross-cutting networks compared with the Kamutile Hills (Fig. 16). No dike ages have been published, but five K-Ar whole-rock ages from related lavas from the NKK Hills have been published (Morley et al., 1992; McDougall and Brown, 2009), and indicate that volcanism lasted from 15 to 13 Ma (Table 2).

The well-developed dike swarm of the Kamutile Hills (Fig. 17) lies in the large-scale relay ramp between the Kerio Basin bounding fault to the southeast (Lothidok-Lokhone fault zone) and the Turkana fault to the northwest (Fig. 16). The dikes exhibit the following patterns (Figs. 17, 18): (1) a strong overall north-south trend over a 13 km

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**Figure 13.** Early-middle Miocene dike patterns in the Lojamei area, overlain on satellite image with 80% opacity over a shaded-relief map. See Figure 2 for location. Rose diagram shows dike orientations measured for 100 m long segments, for 115 km total length of dikes. Lower hemisphere stereonet for 14 fault orientations is also shown. “TVK” numbers are seismic line numbers (see Morley et al., 1999a). A–R are field localities described in detail in the Supplemental Files (text footnote 1).
distance, with the north-south trend as the long axis of a radial dike pattern; (2) a concentric dike pattern, particularly on the western side of the trend; (3) a WNW-ENE trend, particularly in the northern half of the dike field; and (4) a NNE-SSW trend in two en echelon zones.

Notes from one field stop (from 1987) at the northern edge of the dikes (Fig. 17, location X) describe outcrops along a lugga which expose purple, white, and light green pyroclastic rocks (tuffs, lapilli tuff, welded tuffs) interbedded with basic and intermediate lava flows. The sequence locally dips north, but is also locally rotated at intrusions, including intrusions along faults. Dikes vary in composition from black basalts to gray to bluish-gray trachytes and pyroclastic dikes. The dikes are commonly porphyritic and include various combinations of feldspar, biotite, amphibole, and clinopyroxene phenocrysts. Several cross-cutting generations of dikes are present. Dikes occur at a density of eight to 15 dikes per 100 m, range in thickness from 0.5 m to 4 m, and occupy ~20% of the section. Dikes vary widely in orientation, but trends of N10°–N135° and N350°–N010° are the most common. This field locality appears to be broadly representative of the zone affected by dikes.

At the center of the concentric and radial dike pattern is a region of white sediment and pyroclastic rocks, ~2 km in diameter, that is punctuated by numerous volcanic cones (~200 m in diameter) (Fig. 17). This region is a minor depression that has trapped sediment that overlies and masks the dikes. Possibly the depression represents minor subsidance associated with the concentric dikes, caused by deflation of the underlying magma chamber. North of this area is the highest density of dikes in the trend (Figs. 17, 18); dike orientations on satellite images are highly varied, but north-south and NW-SE trends dominate (Fig. 17).

Southern Extension of the Turkana Fault and the Lokhone Basement High (Footwall Uplift)

The area of dikes in Figure 17 is a relatively low-relief region, in contrast to higher-relief areas.
The volcanic rocks of the NKK hills unconformably overlie the Precambrian basement on a sub-horizontal surface that lies at ~580–600 m elevation. Figures 16B and 16C are topographic profiles across the central part of the Kathigithigiria Hills showing the nature of the volcanic edifice that lies as much as ~400 m above the unconformity level with basement. The presence of dikes in the synthetic transfer zone between the Turkana fault and the Lothidok-Lokhone fault zone, and the volcanic high centered along strike of the Turkana fault, strongly suggest that syn-rift fault-related pathways were important for the migration of magma in the NKK Hills area.

The NKK Hills north-south dike trend (Figs. 16, 17) and the NNE-SSW–striking Turkana fault (Fig. 16) converge toward the south and end at a large eroded volcanic cone ~2 km in diameter with a present-day relief above the basement-volcanic unconformity of >250 m (location U, Fig. 19C). South of the volcano, there is no indication of related intrusions in basement exposures. Despite the close proximity to the Kathigithigiria Hills, intrusions in the basement are few, demonstrating the localized nature of the Miocene intrusive activity. Figure 19B shows a rare example for the Lokhone high, where an almost completely eroded Miocene basal outlier on basement reveals a central pipe associated with short (<200 m long) NW-SE– and NNE-SSW–trending dikes. The main indications of any basement influence on intrusions are shown in Figure 19C, where a few short dikes (<200 m) strike NNE-SSW, parallel to basement foliation. Two longer (>1 km) east-west–trending dikes cross-cut foliation. The southern east-west dike does not appear to be associated with any offset or deflections in foliation across the dike, but the northern dike does show such features (Fig. 19D), indicating that it is following a preexisting fault.

**Muranachok-Muruangapoi Area**

In the Muranachok-Muruangapoi area, there are three main mappable units: Precambrian gneisses, the Muranachok Sandstones (of probably Late Cretaceous or Late Cretaceous–Paleogene age), and Oligo-Miocene volcanic rocks (Fig. 5). The Muranachok Sandstones have yet to be reliably dated. However, their possible equivalents to the north in the Lapur Range are now interpreted to represent episodic deposition from the Late Cretaceous to the Eocene, because in the lower part they contain dinosaur bones, while the upper part of the section displays a transitional relationship with the Turkana Volcanics whose base is radiometrically dated at ca. 37–38 Ma (O’Connor et al., 2011; Tiercelin et al., 2012a). Detrital zircons confirm a Paleogene age for the upper part of the section (Owusu Agyemang et al., 2019). The Turkana Volcanics have previously been dated by Zanettin et al. (1983) and McDougall and Brown (2009) as part of a belt that ranges in age between ca. 36 and 16.3 Ma (Table 2). Unfortunately, it is not possible to be certain of the age of the dikes in the Muranachok-Muruangapoi area within this broad age range. But given that the closest ages to the study area are early Miocene, this seems to be the most likely age for the dikes.

Within the gneisses, dikes are spaced variably, between ~1.2 km and 150 m apart, and trend predominantly NNW-SSE (Fig. 20). Locally, at eroded
In the belt of volcanic rocks to the west, NNW-SSE–trending faults are present on satellite images. The eastern margin of the gneisses is interpreted to be bounded by the northern continuation of the Lokichar fault (Figs. 2, 20). Overall NNW-SSE–trending faults and dikes are superimposed on NNE-SSW–trending fabrics in basement (Fig. 2). These igneous features and normal faults are interpreted as being indicative of a NNW-SSE–trending maximum horizontal principal stress ($S_{Hmax}$) direction, probably during the early Miocene.

North of the dikes, Muranachok Sandstones, and the Precambrian gneisses are outcrops of Oligo-Miocene volcanic rocks, which in places have low-relief, well-developed circular to oval patterns (Fig. 20). These volcanic rocks are a mixture of lavas, pyroclastic rocks, volcaniclastic rocks, and minor intrusions (sills, small dikes, and some vent agglomerates). Bedding dips gently (5°–10°) away from the center of the circular patterns, indicating an eroded dome pattern. Some of the features are perfectly circular, while others are asymmetric (Figs. 20, 21) and both are ~1–4 km in diameter. The patterns suggest eroded volcanoes, yet on satellite images there are no clear intrusive complexes (dikes, pipes) in the centers of many of the features (Fig. 21). Hence, at least some of the domes are forced folds associated with underlying sill complexes or laccoliths (e.g., Le Bas, 1971; Pollard and Johnson, 1973; Acocella et al., 2001; Magee et al., 2013, 2017; van Wyk de Vries et al., 2014).

Muranachok-Lapur Range and the Kataboi Fault Zone

The Muranachok-Muruangapoi area displays a very straightforward pattern of dikes and faults that indicate a NNW-SSE $S_{Hmax}$ direction. The complexity in this area lies in the presence of very different trends of faults and dikes in the adjacent area to the northeast (Fig. 2). Vetel (2005) identified a corridor of NE-SW–trending faults that runs from the southwestern Lapur Range to the northern Lothidok Basin, which he called the Kataboi fault zone. According to...
Vetel (2005), the Kataboi fault zone is ~20 km wide and comprises a network of ~N50° faults. Synkinematic volcanic rocks related to small basins with the fault zone have been radiometrically dated to between ca. 28 Ma and 25 Ma (Ragon et al., 2018). For the Kataboi fault zone region, Ragon et al. (2018) interpreted three stages of development. The first extensional pulse is marked by 28–25 Ma; they attributed the non-optimal structural orientations to be due to reactivation of preexisting structures. A period of relative tectonic quiescence is marked by 25–14 Ma, accompanied by development of a significant weathering profile. At 14 Ma, there was the development of a large north-south–oriented half graben called the North Lokichar Basin accompanied by north-south–trending dikes (Boone et al., 2018a). This represents the main phase of rifting, with the basin undergoing changes in morphology between 4.2 Ma and 0.7 Ma (Boone et al., 2018a; Ragon et al., 2018). Further north, ~2 km south of Lokitaung Gorge, there is another NE-SW fault trend (Fig. 2). This trend is accompanied by NE-SW– and NNE-SSW–trending dikes and a later set of cross-cutting north-south dikes, all lying north of the fault trend. Tiercelin et al. (2012a) dated several dikes in this area to between 29 and 27 Ma (Table 2).

DISCUSSION

Origin and Types of Dike Geometries in the Turkana Area

In this study, the areas of well-developed dikes coincide with the tips of major faults or transfer zones between faults (Figs. 2, 13, 16, 19). In the Muranachok-Muruangapoi and Napadet Hills areas, the NNW-SSE– to north-south–trending dikes and faults ignore the NNE-SSW– to NE-SW–trending basement fabric; this suggests that the trends followed the regional $S_{max}$ direction at their time of formation. In the Lokhone high area, the intensity of intrusions is low, but most of the intrusions that are present ignore any basement fabrics (Figs. 15, 19). However, in Figure 19, a few examples are shown where short dikes follow the NNE-SSW trend of basement foliations, and one east-west dike follows...
an older fault (Fig. 19D). In general, the dikes in the study area appear to be more influenced by local and regional stress directions than by basement fabric.

In the Muranachok-Muruangapoi area, NNW–SSE–trending dike swarms lie subparallel to extensional faults and the alignment of eroded circular to oval volcanic features (eroded volcanoes and/or forced folds above sills and laccoliths). This is also the case for north-south– to NWW–SSW–trending early–middle Miocene dikes in the Moiti-Jarigole area (Fig. 2; Supplemental Files [footnote 1]; Wilkinson, 1988). These represent the simplest arrangement expected for syn-rift faults and igneous features. In two areas, the NKK Hills and Loriu, well-developed dike swarms are elongate in a north-south direction that is parallel to the expected regional *S*<sub>max</sub> direction. In both of these examples, the dike swarms are modified from simple subparallel orientations. In the Loriu area, a well-developed radial pattern about a volcanic center is present, while in the NKK Hills region, concentric and weak radial patterns are developed, particularly on the western side of the swarm.

Radial and circumferential patterns tend to arise as a consequence of the interplay between stresses arising from overpressure in the magma reservoir, magma chamber shape (Gudmundsson, 2006; Tibaldi, 2015), surface loading by volcanic edifices (Pinel and Jaupart, 2003), and regional stresses (e.g., Nelson et al., 1992; Pollard and Aydin, 1984; Olson and Pollard, 1991; Tentler, 2003; Muirhead et al., 2015), as well as by magma chamber inflation and collapse (Harker, 1904; Bailey et al., 1924; Anderson, 1942; Phillips, 1974; Bistacchi et al., 2012). For an individual volcanic center, the transition from numerous small volcanic cones to large volcanic edifices with relief >1 km affects dike development due to the changing topographic load with time (Pinel and Jaupart, 2003). Hence the roles played by magma reservoir size, geometry, and overpressure and by topographic load in influencing dike patterns evolves with time (Pinel and Jaupart, 2003). The more regional effects of topographic loads, including rift flank loads, on intrusion distribution are described by Maccaferri et al. (2014). The volcanic fields in the NKK Hills, Lojamei, and Loriu comprise numerous small cones, most commonly <1 km diameter, and even at the center of the radial dike complexes, those in the concentrated area of small cones are <2 km diameter. The highest demonstrable edifice is the Kathigithigiria Hills, where the extrusive activity of small volcanic cones has built a high as much as ~400 m thick above basement. But even this relief falls short of the 1 km relief considered as exerting a significant load by Pinel and Jaupart (2003). The footwall of the Lokichar fault, which today is of very low relief, shows low amounts of exhumation that occurred over a long time period (cooling of ~100 °C gradually over a 40 m.y. time period; Boone et al., 2018b, 2019), suggesting that topographic relief was never very high (i.e., <1 km), an inference supported by the relatively limited development of boundary-fault alluvial fan deposits adjacent to the Lokichar fault in the Lokichar Basin (e.g., Morley et al., 1999a; McClymont, 2018). Consequently, for the stages outlined above, the dikes in the Kathigithigiria Hills and Loriu are interpreted to have developed in an area of relatively low topographic relief, where the effects of volcanic edifice building...
and rift flank topography were limited. In turn, this suggests that the circumferential and radial dikes were influenced by regional stresses and magma reservoir size, geometry, and overpressure, rather than topographic load.

In the case of the Loriu-area high-density dike zone (area B in Fig. 10), there is a pronounced NW-SE trend, which is oblique to other dikes and structural trends in the area, including NNE-SSW–trending Precambrian gneisses (Fig. 2). The short length (average 0.3 km) and narrow width (<1 m) of the dikes suggest that they are sourced from a shallow magma reservoir. In area B in the Loriu area, dike spacing is 21.5 dikes per kilometer, and dike length is between 25 and 660 m. Dike thickness is generally <1 m, but even using 1 m dike thickness, extension is low, <2%, or a total of 64.5 m extension over the 3-km-wide area in which they are present. One interpretation that accounts for the shallow depth source for the dikes, the trend of the dikes, and the anomalous WNW-ESE strike and NNE dip to the boundary between the sandstones and the Precambrian basement, is a sill or laccolith-like body within the area of Precambrian gneisses outcrop that passes to the northeast to a region where the laccolith is less inflated (or has been deflated) in the vicinity of the NW-SE–trending dikes (Fig. 11). Some of the NE-SW–trending faults related to the radial fault trend are superimposed on the NW-SE trend. The proposed formation of dikes of variable orientation above a sill or laccolith is analogous to the cracked-lid model, where dike networks are fed by a sill and form above the sill, and the dike patterns...
are related to sill emplacement processes, not far-field stresses (e.g., Muirhead et al., 2014; Coetzee and Kisters, 2017).

The South Lokichar Basin exhibits networks of highly variably oriented dikes, which could fit a cracked-lid model (Muirhead et al., 2014; Coetzee and Kisters, 2017). However, the dike network was built up over an ~6 m.y. time span, and the large aspect ratios (3–5 km long, 5–10 m wide) of some dikes suggest a relatively deep magma source. Hence the cracked-lid model seems less applicable for the Lojamei area than the Loriu. Many more dikes need to be dated to determine whether there are systematic changes in dike orientation with time, or whether multiple trends are associated with each period. Of the four study areas, Lojamei exhibits the widest dikes (~10 m). Average dike spacing in the areas most heavily intruded is about eight dikes per kilometer, which would indicate a maximum of 80 m extension per kilometer if all dikes were 10 m thick (~9% extension). Thicknesses cannot be measured accurately from satellite images, but the proportion of narrow dikes (<2 m) to wide dikes (5–10 m) is ~8:1, suggesting that 2 m is a more appropriate average than 10 m, which gives 16 m/km extension (~1.6% extension).
Comparison of Dike Development in Turkana versus Southern Kenya and Ethiopia

The southern Kenya and northern Tanzania rift system represents a young (<7 Ma), well-documented, low-extension active rift system, and it is an example where mantle processes control the extension of thick, initially cold lithosphere (e.g., Muirhead et al., 2016; Roecker et al., 2017; Plasman et al., 2017; Tiberi et al., 2019). The region exhibits continental crust with an upper-crustal volcanic plumbing system that is interpreted to be dominated by a volatile fluid-rich in CO$_2$ (>5–15 km depth) accumulated at the top of crystal-rich magma mush–filled chambers, while a network of molten rock lies in the lower crust and upper mantle (Fig. 22; e.g., Roecker et al., 2017; Ebinger et al., 2017). Mid-crustal-level and lower-crustal magma storage areas are interpreted to be dominant, with major dike systems being mostly fed from lower-crustal reservoirs and accommodating significant extension even at an early stage in the rift history (Roecker et al., 2017; Plasman et al., 2017; Tiberi et al., 2019).

For the Magadi area of the southern Kenya Rift, Muirhead et al. (2016) estimated that the border faults accommodated regional extension at rates between 1.23 and 1.78 mm/yr for the first 3 m.y. By 7 m.y., the smaller intra-rift faults had taken over much of the extension (1.34–1.60 mm/yr), along with magmatic volatile release occurring in the rift center and intrusion of dike swarms at depth (Muirhead et al., 2016). This evolution demonstrates the importance of flow of magmatic fluids within fault systems, and how they weaken the lithosphere and focus upper-crustal strain early in the rift history, even prior to magmatic segments being established (Muirhead et al., 2016). A link between overpressures related to magma (or magma-derived fluids) and modern faulting activity is also suggested by recent GPS (Jones et al., 2019) and earthquake (Baer et al., 2008; Oliva et al., 2019) studies. In particular, where boundary fault–related earthquakes are present down to the base of the crust (~42 km depth in southern Lake Tanganyika), rapid stressing of faults due to active magmatic intrusions or related volatile-rich fluids may cause brittle deformation in crust that is ductile at lower strain rates (Fagereng, 2013; Hodgson et al., 2017; Lavaysière et al., 2019).

The Main Ethiopian Rift is a more mature magma-dominated extensional system than the southern Kenya Rift, where 80% of the extension across the Main Ethiopian Rift is confined to ~20-km-wide magmatic segments dominated by dike injection and related faulting (Hayward and Ebinger, 1996; Ebinger and Casey, 2001; Keir et al., 2006). Swarms of low-magnitude earthquakes are concentrated at 8–14 km depth, and coincide with the top of a 20–30-km-wide zone of mafic intrusions (Keir et al., 2006). In the brittle seismogenic layer, both faulting and dike intrusions are ongoing, with dikes aligned perpendicular to the minimum stress (Keir et al., 2006). In the Main Ethiopian Rift, diking, not extension on bounding faults, is the dominant mechanism for extension, which occurred at a rate of 4.0 ± 0.9 mm/yr between 1992 and 2003 CE (Bendick et al., 2006). Within the dike swarms, individual dike widths are typically ~0.5–1.5 m, but dike activity tends to be cyclic, and the first dikes in a cycle tend to be wider (~5–6 m; Wright et al., 2006).

The rift system in Turkana contains elements of active rift development as determined for the southern Kenya and Main Ethiopian Rifts outlined above, but also diverges in important ways. The tectonic evolution of the Turkana–southern Ethiopian Rift from the onset of magmatism is shown in Figure 23. The first phase of magmatism (40–23 Ma) was focused on southern Ethiopia and northwestern Turkana (Figs. 3, 23D) and, as discussed in the Geological Background section, is plume related and affected by minor crustal extension (Hendrie et al., 1994). This early plume-related magmatism did not, however, result in Turkana progressing rapidly to a magma-dominated system like the southern Kenya Rift. The area covered by late Paleogene volcanic rocks in northern Kenya is substantial (~42,000 km$^2$; Morley, 1994). However, to the south and southeast, there is a large region of late Paleogene–early Miocene extensional basins filled by

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**Figure 22.** Schematic cross-section illustrating the early stage of continental extension in an active rift (e.g., southern Kenya Rift). Uplift of the asthenospheric mantle (due to development of a thermal anomaly and/or extensional thinning of the lithosphere) has progressed to a stage where there is a large supply of magma to the central part of the rift, and so extension by dike intrusion is in the process of replacing shear failure along large faults as the dominant mode of extension. X — deep seismicity associated with brittle displacement along boundary faults (e.g., Ebinger et al., 2017). Upper crust shows faulting, infiltration of CO$_2$-rich fluids from the lower crust, small magma chambers, and numerous small intrusions; lower crust demonstrates some faulting, large crystalline mush–filled chambers, extension mostly accommodated on axial dike complexes, and magmatic underplating in basalt part of crust. The classic upper (brittle)–lower (ductile) crust boundary is blurred by the occurrence of deep earthquakes (e.g., those indicated by X) in old Precambrian crust that was cold at the start of rifting. Deep earthquakes may be related to lower-crustal composition and/or overpressuring by fluids related to magmatism. Conversely, heat flow in the crust is elevated by crustal thinning, igneous intrusions, and convecting hydrothermal fluids. Based on data from Ebinger et al. (2017), Plasman et al. (2017), Roecker et al. (2017), and Tiberi et al. (2019).
Figure 23. Tectonic development of the Turkana–southern Ethiopian Rift area during the late Eocene–recent. Compiled from information in Morley et al. (1999a), Ebinger et al. (2000), Vetel (2005), Vetel and Le Gall (2006), Balestrieri et al. (2016), Emishaw et al. (2017), McDougall and Brown (2009), Brown and Jicha (2016), and Rooney (2017). The Gatome Basin (panel D) is an older basin of probable Late Cretaceous–Paleogene age that underlies the late Eocene–Oligocene volcanic rocks. CB—Chew Bahir Basin; J—Jibisa; LB—Lokichar Basin; OB—Omo Basin; TB—Turkana Basin; TuB—Turkwell Basin. KSFB—Kino Sogo fault belt; SV—Suguta Valley Pliocene–Holocene volcanic centers (panel A) mapped from satellite images in this study: AV—Asie volcanic centers; DV—Dukana volcanic centers; HV—Hurri Hills volcanic centers; KV—Kulal volcanic hills; MV—Marsabit volcanic centers. Extension direction estimates: 1—Kataboi fault zone area, activity ca. 28–25 Ma (Ragon et al., 2018). 2—Lojamei area; inferred from dip-slip normal faults to be approximately east-west extension; dike orientations are variable and suggest local perturbation of the stress field by magma chambers ca. 17–15 Ma, and more north-south–oriented dikes and approximately east-west extension direction during the 12–10 Ma period of dike emplacement (panels B and C; see the South Lokichar Basin–Lojamei Area section in text). 3—Loriu area; from dike orientations suggesting east-west extension direction (minimum horizontal stress), with strong local stress field perturbation by magma chambers (panel C; see the Loriu Area section in text). 4—Muranachok–Muruangapoi, from fault and dike trends (panel C; see Muranachok–Muruangapoi Area section in text). 5—Napadet–Kamutile–Kathigithia–Hills; from north-south dike trends, plus local stress field perturbation by magma chambers (panel B; see Napadet–Kamutile–Kathigithia–Hills section in text). 6—Minimum horizontal stress direction orthogonal to strong NE-SW to NNE-SSW trend of small volcanic cones and craters (see Discussion section) of AV, DV, HV, and MV for the Pleistocene (panel A; Strecker and Bosworth, 1991). Recent extensional activity (red arrows) as indicated by seismicity and deformed Holocene lake shorelines appears to be focused along the trend of Suguta Valley and Lake Turkana (panel A; Pointing et al., 1985; Melnick et al., 2012). Details of Cenozoic activity within the Anza Graben are not shown, but in general, Paleogene activity (panel D) is more important in the central and southeastern part of the graben, while Neogene activity (panels B and C) was significant in the northwestern part (Morley et al., 1999b). When passively subsiding, it was still an important depression and exerted an influence on drainage; during sea-level highstands, it acted as a marine gulf, apparently enabling an unfortunate whale to be preserved amongst freshwater fossils in the Loperot area of the Lokichar Basin, Turkana (Wichura et al., 2015).
continental, basement-derived sediments, where igneous activity was absent until the early Miocene (Fig. 3; Morley et al., 1999a). The Lokichar Basin and possibly the Turkana Basin (Fig. 2) represent the northern limit of these syn-rift basins, which extend 300 km south to the Tugen Hills–Elgayo escarpment area (Kamego Formation; see review in Muia [2015]). Sandine grains from a phonolite interfingering with the top of the Kamego Formation in the Tugen Hills yielded \(^{40}\)Ar/\(^{39}\)Ar ages (19.9 ± 0.1 Ma, 19.8 ± 0.1 Ma), that place the end of dominantly basement-derived syn-rift sedimentation as <20 Ma (Muia, 2015). The 300-km-long (north-south) belt of rift basins, with minor to no volcanic input until the early Miocene, indicates that rift tectonics progressed differently over an ~25–30 m.y. period, compared with the last 7 m.y. for the southern Kenya Rift (as summarized in Fig. 22). The onset of volcanism at ca. 18–20 Ma (Tatsumi and Kimura, 1991; Morley et al., 1999a; Muia, 2015) above basins filled by basement-derived sediments is a significant feature of the 300-km-long belt. On the eastern side of Lake Turkana are notable early–middle Miocene volcanic rocks around Moiti-Jarijogole and the Jbisia ring complex, which include basic lavas and syenite intrusions (e.g., Wilkinson, 1988; Key, 1989; Furman et al., 2006). The early extension in Turkana overlaps with minor periods of late Paleogene extension in the Sudan and Anza rifts to the northwest and east respectively (e.g., Schull, 1988; Key, 1989; Furman et al., 2006). The distribution of these basins over an area ~1800 km in a NW-SE direction and >400 km wide, and oblique to the more north-south trend of the Eocene–Oligocene volcanic rocks in southern Ethiopia and northern Turkana (Fig. 1B), suggest that far-field stresses, not just those arising from active rifting, could have played a role at least during the early stages of rift formation in central Kenya and Turkana.

Extension and deposition in the predominantly Oligocene–middle Miocene–age Lokichar Basin (Morley et al., 1999a) is dominated by the east-dipping boundary fault, which exhibits as much as 14 km of heave (Morley et al., 1999a), indicating time-averaged extension rates of ~0.56 mm/yr for the 25 m.y. duration of rifting. If at times more than one basin lateral to the Lokichar Basin (e.g., Turkwell and/or Kerio Basins) was also active (but with lower heaves), possibly rates could have been ~1 mm/yr. Such rates are in line with modern geodetic rates across the whole East African Rift, which indicate predominantly east-west extension with an angular velocity of 1.99 mm/yr (Stamps et al., 2018) and are of similar magnitude, but lower than, estimates of border-fault displacement from the southern Kenya Rift (Muirhead et al., 2016). However, unlike in the southern Kenya Rift, there is no evidence for an inner fault zone or a segmented magmatic axial belt developing at this time, and magmatism played a very minor role at least in the upper crust in southern Turkana until the early Miocene (23–15 Ma; Fig. 23C).

The areas of well-developed dikes described in this study are of early–middle Miocene age, and are representative of the first time during the syn-rift stage when significant quantities of magma encountered well-developed systems of extensional faults in the upper crust. In the Moruerith and Lothidok Hills areas (Fig. 5), there is overlap between the regions with late Eocene–Oligocene volcanism and those with Miocene volcanism (Fig. 23B), but over much of the area, the first entry of volcanism into the rift occurred ca. 18–20 Ma and volcanism continued until ca. 10 Ma (Figs. 3, 23). More extensive dating of dikes is required to determine in detail what patterns in magmatic behavior may exist in the region. The short lateral extent of the area of intense dike intrusions (<15 km), the minor, highly local contribution to upper-crustal extension (<2%), and the overall area affected by volcanism (~13,150 km²) indicate that igneous activity was relatively localized and of low volume. The dike systems described for Turkana are noticeably shorter, thinner and more closely spaced and occupy a smaller area than those described for the Oligocene of the Main Ethiopian Rift (Fig. 24). The presence of pyroclastic dikes in the NKK Hills indicates a close association of the dikes with the shallow plumbing systems of volcanoes (e.g., Torres-Hernández et al., 2006). The graph plots of length-thickness variations exhibited by the Turkana dikes match with results of a previous comparison of dike lengths that included examples from Ethiopia (Fig. 25; Cruden et al., 2018), with similar length:thickness ratios being observed, but where the longest dikes in Turkana are about an order of magnitude shorter than the longest dikes in Ethiopia.

The 6 Ma–recent period in Turkana is marked by inner rift–style faulting, which trends NNE-SSW from Suguta Valley in the south, through southern Lake Turkana, to the Kino Sogo fault belt–Chew Bahir Rift in northern Kenya and southern Ethiopia (Fig. 23A). The volcanism is narrowly focused in Suguta Valley and expands toward the north to cover a large area from Lake Turkana in the west to the Hurri Hills and Mount Marsabit in the east (Fig. 23A). This volcanism is part of the regional trend in the Kenya Rift where the erupted volume increases from a range of 2800–1000 km³/m.y. during the Miocene to 7300 km³/m.y. during the Pliocene–Holocene (Guth, 2015). In the Hurri Hills and Mount Marsabit areas, the trends of the volcanic edifices and their volcanic cones and craters indicate NNE-SSW–to NE-SW–trending \(S_{\text{max}}\) directions or NW-SE to NNW-ENE extension directions during the Pleistocene (Fig. 23; Strecke and Bosworth, 1991). However, present-day extension in the region is NW-ENE to west-east (Stamps et al., 2018), with Holocene and modern extension rates across the southern Lake Turkana–Suguta Valley area estimated in the range of 3.2–6.7 mm/yr (Melnick et al., 2012) and 4.3–5.1 mm/yr (Stamps et al., 2008; Knappe et al., 2020). Mantle xenoliths from the Mount Marsabit volcanics record different stages in mantle evolution, with evidence for non-rifted sub-continental lithospheric mantle, a cooling and decompression stage related to Anza Graben rifting, and a subsequent stage of magmatism and metasomatism related to Quaternary volcanism, including evidence for infiltration of \(\text{H}_2\text{O}-\text{CO}_2\)-rich silicic melts (Kaaser et al., 2008).

The development of a Plio-Pleistocene igneous trend east of the region of maximum crustal thinning (Fig. 4) suggests that by Pleistocene, mantle processes, akin to those affecting the southern Kenya Rift (see Fig. 22), had come to dominate extension in Turkana. Although some short-lived extensional trends have affected the area east of Lake Turkana in the Plio-Pleistocene (Kino Sogo fault belt, Ririba Rift; Fig. 23), the area of consistent extension during this time has been Lake Turkana (Morley et al., 1999a;
Figure 24. Comparison of the size of dikes from Turkana (this study) (A) and those associated with Oligocene flood basalts in the northern Ethiopian Rift (redrawn from Rooney et al., 2018) (B). Dike colors in B are: red—ENE-WSW trend; green—NW-SE trend; black—radial and concentric dikes around volcanic center.

Figure 25. Log thickness versus log length for igneous dikes, from Cruden et al. (2018) with Turkana data added.
CONCLUSIONS

Well-exposed dikes in western Turkana are described in detail for the first time in this study. The early-mid Miocene dikes and extrusive faults ended a long phase (as long as 25 m.y.) of magmatic half-graben development in central Kenya and southern Turkana, which lay on the southern edge of the early (Eocene–Oligocene) plume activity. A wide range of dike patterns (parallel, circumferential, radial, cross-cutting networks, superimposed trends) are present. In places (Loriu, Lojamei, Lokhone high), dikes trend a high angle to the rift trend, suggesting some local influence (e.g., overpressured magma chamber, cracked lid-style dike intrusions over a sill or laccolith, preexisting fabric in basement) on orientation as well as the influence from regional stresses. Despite diverse dike orientations being present, the overall north-south to NW-SEE dike trends are supportive of approximately east-west extension during the early-middle Miocene.

The early to middle Miocene-age dikes occur in localized areas as much as ~15 km long and 5 km wide, are closely spaced (tens of dikes per kilometre), relatively short (<5 km), and numerous (>3500 dikes have been mapped), and have only accommodated low amounts of upper-crustal extension (<2%). This limited development of dikes differs from the larger, more extensive arrays of dikes in evolved systems in the Main Ethiopian Rift that are critical for accommodating crustal extension. Instead, in the Oligocene–Miocene Turkana Rift basins, extension was primarily accommodated along the very large border faults. The early style of rifting contrasts both with the development of other parts of the Eastern Rift Branch and with the Pliocene–Holocene style of rifting around and east of Lake Turkana, where magmatism and dikes have become more important for accommodating extension, and smaller fault swarms have tended to develop (although some larger boundary faults in Lake Turkana continued to be active).

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