Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 265 (2008) 466–474
EPSL
www.elsevier.com/locate/epsl

Why meter-wide dikes at oceanic spreading centers?

Ran Qin *, W. Roger Buck

Lamont-Doherty Earth Observatory of Columbia University, United States

Received 11 October 2006; received in revised form 13 October 2007; accepted 17 October 2007
Available online 1 November 2007
Editor: C.P. Jaupart

Abstract

Numerical models show that maximum dike width at oceanic spreading centers should scale with axial lithospheric thickness if the pre-diking horizontal stress is close to the Andersonian normal faulting stress and the stress is fully released in one dike intrusion. Dikes at slow-spreading ridges could be over 5 m wide and maximum dike width should decrease with increasing plate spreading rate. However, data from ophiolites and tectonic windows into recently active spreading ridges show that mean dike width ranges from 0.5 m to 1.5 m, and does not clearly correlate with plate spreading rate. Dike width is reduced if either the pre-diking horizontal stress difference is lower than the faulting stress or the stress is not fully released by a dike. Partial stress release during a dike intrusion is the more plausible explanation, and is also consistent with the fact that dikes intrude in episodes at Iceland and Afar. Partial stress release can result from limited magma supply when a crustal magma chamber acts as a closed source during dike intrusions. Limited magma supply sets the upper limit on the width of dikes, and multiple dike intrusions in an episode may be required to fully release the axial lithospheric tectonic stress. The observation of dikes that are wider than a few meters (such as the recent event in Afar) indicates that large tectonic stress and large magma supply sometimes exist.

Keywords: dike; width; mid-ocean ridges; magma supply; dike episode; magma chamber

1. Introduction

Dikes are planar cracks filled with magma. In oceanic spreading centers, either back-arc spreading centers or mid-ocean ridges, basaltic dikes intrude repeatedly and form most of the oceanic crust (Delaney et al., 1998; Einarsson and Brandsdottir, 1980; Fialko and Rubin, 1998; Kidd, 1977; Sohn et al., 1998). Dike intrusions release magma and volatiles into the ocean, perturbing hydrothermal vents and triggering a sequence of related physical, chemical, and biological processes (Delaney et al., 1998). Given the central role of dike intrusions in plate spreading and related biological processes, sheeted dikes in ophiolites representing ancient oceanic crust have been extensively studied (Kidd, 1977). In recent years technological improvements also have made real-time monitoring and on-site experiments to study dike intrusions at active oceanic spreading centers possible.

The planar geometry of a dike makes the dike width as an easy-to-measure parameter that permits the most direct comparison between theoretical predictions and field observations. For example, dike width is directly tied to the frequency of dike events in a ridge of given spreading rate, which is essential for us to plan on-site experiments

* Corresponding author. LDEO 305 Oceanography, 61 RT. 9W, Palisades, NY10964, United States.
E-mail address: rqin@ldeo.columbia.edu (R. Qin).

0012-821X/$ - see front matter
doi:10.1016/j.epsl.2007.10.044

at spreading ridges. Dike width is also thought to be a key factor controlling dike thermal cooling rate, dike propagation distance and speed and the persistence of fissure eruptions (Bruce and Huppert, 1989; Fialko and Rubin, 1998; Lister, 1995). These factors are essential to the understanding of ridge segmentation and magma transportation and distribution along ridge axis.

As we will detail below, basaltic dikes are nearly meter-wide, on average, across all oceanic spreading centers where field data are available. Though various processes may affect the width of a basaltic dike (Valentine and Krogh, 2006), it is generally accepted that basaltic dikes at oceanic spreading centers open as a result of elastic expansion of host rock under magma overpressure (Fialko and Rubin, 1998; Lister, 1995; Pollard et al., 1983). Since oceanic spreading centers have different thermal and mechanical structures (Purdy et al., 1992), it is important to know why the dike widths across different tectonic settings have the same average. However, previous studies calculating dike width by simply assuming 10–20 MPa uniform driving pressure failed to account for tectonic conditions, including the variations of driving pressure and dike height across different spreading centers (Fialko and Rubin, 1998; Pollard et al., 1983; Rubin, 1990; Rubin and Pollard, 1988).

Rather than treating a dike as a uniformly pressurized crack in an elastic half-space, in this study we compute possible stress distributions before and after dike intrusions in a way that accounts for a reasonable strength structure of the spreading center and the level of magma supply from magma chamber. Another advantage compared with previous studies is that we calculate the dike top and bottom using Weertman's method (Weertman, 1973) and do not assign the dike an arbitrarily determined dike height. We will show that limited magma supply controls the dike width.

2. Statistics of field data on dike width

Dike width measurements from active and fossil spreading centers (mid-ocean ridges and back-arc spreading centers) are readily available. In this study we use data from ophiolites from Oman (Umino et al., 2003), Troodos (Kidd, 1977), Betts Cove (Kidd, 1977) and Bay of Islands (Rosencrantz, 1983) in Newfoundland, Josephine of California (Harper, 1984), Ballantrae in Scotland (Oliver and McAlpine, 1998) and ancient dike swarms in Iceland (Gudmundsson, 1983; 1995); dike events monitored during Krafla 1975–1985 in Iceland (Tryggvason, 1994) and dikes exposed at Hess deep (unpublished data, J. Karson). Since September 2005, several dikes have intruded along the Dahabbu segment in Afar, East Africa (Wright et al., 2006).

Table 1 shows the number of dikes collected from these areas, inferred spreading rate, and the mean dike width. Since the dike width has either a power-law or log-normal distribution (Gudmundsson, 1983; 1995; Kidd, 1977; Rosencrantz, 1983), standard error is not a good description and we arbitrarily choose an upper band of dike width to help indicate dike width distribution, within which 80% of the dike measurements lies. The dike width is defined as the space between two chilled margins that indicates a single dike intrusion or 2 times the width if one chilled margin is missing (Kidd,

Table 1
Statistics of data on dike thickness

Spreading center	Inferred spreading rate [a]	Mean width (m)	Upper limit that contains 80% data (m)	Number of measurements
Hess Deep [b]	13 cm/yr, fast	0.56	0.64	37
Oman ophiolite (Umino et al., 2003)	Intermediate to fast	0.71	1.3	1511
Troodos ophiolite (Kidd, 1977)	Intermediate	1.58	2.4	530
Josephine ophiolite (Harper, 1984)	Intermediate to slow	~0.60	N/A	>600
Ballantrae ophiolite (Oliver and McAlpine, 1998)	N/A	0.50	1.03	137
Newfoundland ophiolite	Slow	0.48 (Kidd, 1977)	0.7	190
		0.80 (Rosencrantz, 1983)	1.2	576
Iceland	2.0 cm/yr, slow	0.8 (Tryggvason, 1994)	1.0	9
		~1.0 [c] (Gudmundsson, 1995)	~2.0	>5000
Afar, East Africa Rift	1.0 cm/yr, slow	<5.0–6.0 [d]	/	Several

[a] Fast means full spreading rate>8 cm/yr, slow means<4 cm/yr and intermediate falls between.
[b] Unpublished data from J. Karson.
[c] Tertiary dike swarms, A. Gudmundsson, pers. comm.
[d] Dike swarm recorded beginning September 2005.